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Degree:	Masters of Science
Year This Degree Granted:	2003

University of Alberta

Development of a Lean Approach in Simulation Using Surface Works Operations of Road Construction

by

Jack Michael Farrar ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Masters of Science

in

Construction Engineering and Management
Department of Civil and Environmental Engineering

Edmonton, Alberta

Spring 2003

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **"Development of a Lean Approach in Simulation Using Surface Works Operations of Road Construction"** submitted by **Jack Michael Farrar** in partial fulfillment of the requirements for the degree of Masters of Science in Construction Engineering and Management.

Dedication

This thesis is dedicated to my family and friends who provided their valuable strength and support during my studies. I would also like to thank my supervising professor Dr. Simaan AbouRizk for his time, support, and guidance during the course of my research.

Abstract

Lean production theory as a production management tool, describes a system that delivers a finished product that is free from defects, to a customer in zero time, with nothing left in inventory. Lean production theory can be summarized into three main points; 1) Eliminate or reduce all activities that do not add value to the final product, 2) pull material through the process (instant delivery of required materials), and 3) reduce variability by controlling uncertainties within the process.

This thesis presents a universal approach that will facilitate the implementation of the concepts of lean production theory into computer simulation models and in turn actual construction projects. In order to accomplish this a special purpose simulation template was developed for surface works operations in road construction. This template allows for the creation of surface works road construction simulation models that provide industry practitioners a tool for analyzing, optimizing, and improving construction operations. With respect to this thesis, the template provides a means of testing the concepts of lean production on road construction simulation models to quantify their impact on road construction processes. The results obtained from this exercise are used in the development of the generic approach for the application of lean principles in computer models.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Research Objectives and Background

1.1 Overview

Lean production theory as a production management tool, describes a system that delivers a finished product that is free from defects, to a customer in zero time, with nothing left in inventory. Implementing lean production theory requires a somewhat more detailed set of guidelines, however these can be summarized into three main points; 1) eliminate or reduce all activities that do not add value to the final product, 2) pull material through the process (instant delivery of required materials), and 3) reduce variability by controlling uncertainties within the process. Because lean production theory was developed initially for manufacturing, many of its principles have widely been accepted in that industry. Recently, however, the concepts of lean production have been introduced to the construction industry, and coined lean construction, with mixed reviews.

The construction industry has generally rejected the ideas of lean production mainly due to the belief that construction is somehow different; that it alone has unique and complex projects in highly uncertain environments that are under great time and schedule pressure (Howell, 1999). Although there is some truth to this statement, Howell and Ballard argue, "Manufacturing is a special case of construction because it alone is characterized by multiple copies of the same project". Another reason that lean principles are generally

not accepted is that the construction industry currently has a fundamentally different view of how process improvement is accomplished.

On most construction projects cost reduction results from improving productivity, and project duration is shortened by accelerating activities, or by changing schedule logic to allow for concurrent work. Waste is cost associated with rework, or extended activity duration (Howell and Ballard, 1998). Lean production takes a more global view of the production system. Howell and Ballard describe the difference by stating that "current project management views a project as the combination of activities, lean thinking views the entire project in production system terms, that is, as if they project were one large operation". Historically the construction industry has been very slow to change in many respects, which makes implementing the concepts of lean production theory very difficult. Industry practitioners are wary of implementing new techniques on large complex projects. Implementing a fundamentally different management system on a multimillion-dollar project could be viewed as risky. For this reason, computer simulation provides an excellent environment to implement the principles of lean production, study their effects, and gain a better understanding of how these principles can be applied to real construction projects.

Computer simulation is defined by Pristker (1986) as the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer. Appleton (2002) describes special purpose simulation (SPS) as computer based environment built to enable a practitioner who is knowledgeable in a given domain,

but not necessarily in simulation, to model a project within that domain in a manner where symbolic representation, navigation schemes within the environment, creation of the model specifications, and reporting are completed in a format native to the domain itself. By using SPS tools to create an industry specific modeling environment, computer simulation provides many advantages for industry practitioners including wider acceptance and use in practical settings (AbouRizk, 1998). SPS tools allow the user to interface with a level of the model that is isolated from the low level constructs and that more closely represents the actual system (Hajjar and AbouRizk, 1996). Simphony (Hajjar and AbouRizk), is a simulation platform that can be used to build both general and special purpose simulation tools (Appleton , 2002). Simphony "greatly simplifies the SPS tool development process and standardizes the simulation, modeling, analysis and integration features of such tools. The result is a complete environment that tailors to the needs of both novice and advanced simulation tool developers and users" (Hajjar and AbouRizk, 1999).

1.2 Research Objectives

The first objective of this research is to develop a generic approach that will facilitate the implementation of the concepts of lean production theory into computer simulation models and in turn actual construction projects. More specifically, the second objective of this research will focus on the application of lean production principles to surface works operations of road construction projects. A secondary objective of this research is the development of a special purpose simulation tool that will allow industry practitioners to create computer models of surface works road construction projects that will facilitate

both scenario analysis and lean production principles. The following steps have been identified as necessary in order to achieve the outlined objectives.

1. Research and understand the processes involved with surface works operations of road construction projects, and how they are managed.
2. Extract from the processes of surface works operations, the necessary components required for computer simulation.
3. Develop a special purpose simulation template (SPS) that will allow the creation of computer models of surface works operations in road construction that are flexible and easy to use.
4. Validate the SPS template by using it to create a model of a project that has already been completed, and compare the outputs.
5. Develop a generic approach for the implementation of lean production principles for use in computer simulation models and for actual construction projects.
6. Use the validated SPS template to create models of surface works operations in road construction that will facilitate experiments of the introduction of lean production principles.
7. Outline the findings from applying lean production theory to the simulated operations of surface works in road construction, for use by construction companies.

1.3 Research Methodology

In order to accomplish the fore mentioned objectives, the research was conducted in six steps. The first step involved the understanding of surface works operations in road construction. This was accomplished through discussions with industry practitioners, data collection and time studies, and personal experience. During the summer of 2000 the author, with the cooperation of Standard General Inc. performed several detailed time studies with regard to asphalt paving production rates and productivity. Project managers, superintendents, and foreman contributed information that was essential for the detailed understanding of the process.

The second step was to extract the information collected in such a manner that would help to map the process into logical and mathematical sub-processes. This is a critical step that enables an actual construction process to be translated into a computer simulation environment.

The third and forth steps were the development and validation of a special purpose simulation template that enables users to create flexible models of surface works operations in road construction. This was accomplished using Simphony (Hajjar and AbouRizk), which is a simulation platform that can be used to build both general and special purpose simulation tools (Appleton, 2002). In the fourth step, validation of the SPS template was accomplished by using it to create a model of the Anthony Henday Drive Extension Project, which was completed in 2001 by Standard General Inc. The

model outputs were compared to actual project data, which allowed the SPS template to be validated.

The fifth step in the research was to develop an approach for the implementation of lean production theory in the construction industry. This provided guidelines for the generic implementation of lean principles in simulation models, which can then be further extended into actual processes.

The final step of the research was to use the guidelines from step five to experiment with the concepts of lean production theory with a model created by the SPS template. This allowed the effects of lean concepts on road construction processes to be measured. It also provided valuable insight into the road construction processes, which could not have been performed outside the simulation environment.

1.4 Thesis Organization

This thesis is organized as follows:

Chapter 2 provides a literature review of the state-of-the-art in both lean production principles and computer simulation.

Chapter 3 provides an overview of processes within surface works operations in road construction.

Chapter 4 steps the reader through the development of the special purpose simulation template for the surface works operations of road construction. The templates modeling elements are described in detail, and a description is given on how a model can be created using the template.

Chapter 5 validates the SPS Template using the Anthony Henday Drive Extension Project as a case study. A model is created of the project using the template and the outputs are compared to actual data collected.

Chapter 6 describes a generic approach that was developed for the implementation of lean production concepts in computer models and in turn actual construction projects. The SPS template is used to create models for the purposes of experimenting with the concepts of lean construction. Several key findings are made as a result of the experiments that include how the concepts of lean production theory affect surface works operations of road construction, and how these concepts can be implemented in a computer simulation environment.

Chapter 7 describes the research contributions, conclusions, and recommendations of this thesis research.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a summary of the state-of-the-art in:

1. Lean Production / Lean Construction Theory
2. Computer Simulation
3. Lean Construction and Computer Simulation Models

Section 2.2 summarizes the history and current practice in lean production / construction theory, while section 2.3 summarizes the history and current practice of computer simulation applications and techniques, and section 2.4 presents a brief summary of the work that has been done to combine simulation and lean production theory.

2.2 Lean Production Theory

An Engineer named Taiici Ohno, who worked for Toyota, developed lean production theory. Ohno shifted attention to the entire production system from the focus of craft production on worker productivity, and mass production on machine productivity. Ohno followed the work of Henry Ford and continued the development of flow based production management. (Howell, 1999)

The underlying goal of lean production theory is the avoidance, elimination, or reduction of waste (Howell, 1999). Howell defines waste by the performance criteria for a

particular production system; failure to meet the unique requirements of a client is considered waste. Another definition describes waste as time, space, or material used in the performance of an activity that does not directly contribute value to the finished product. Using these broad definitions for waste, lean production theory attempts to move a production system towards perfection, or zero waste.

Koskela describes the conventional production philosophy as the Conversion Model, which has the following properties:

- A production process is a conversion of an input to an output.
- The conversion process can be divided into sub processes, which also are conversion processes.
- Minimizing the cost of each sub process can minimize the cost of the total process.
- The value of the output of a process is associated with costs (or value) of inputs to that process.

Lean production theory views the production system as a series of conversions and flows. Conversion activities are seen as those, which add value to the final product. Flow activities are those, which transfer the product to and from conversion activities. A main concept of lean production theory is to reduce or eliminate the share of flow activities while increasing the efficiency of conversion activities. The following list outlines the key principles of lean production theory. (Koskela, 1992)

- Reduce the share of non-value adding activities.
- Increase output value through systematic consideration of customer requirements.
- Reduce variability.
- Reduce the cycle time.
- Simplify by minimizing the number of steps, parts or linkages.
- Increase output flexibility.
- Increase process transparency.
- Focus control on the complete process.
- Build continuous improvement into the process.
- Balance flow improvement with conversion improvement.
- Benchmark.

2.2.1 Current Thinking in Construction

The traditional method used to plan and optimize construction projects is by breaking them up into their components. Each activity or operation is analyzed independently from the rest of the project and it is thought that a cost reduction or productivity improvement on each activity will combine to result in an overall improvement of the operation; in many cases this does not occur. This process improvement technique is fundamentally different from that of lean production theory.

Lean Construction Theory is the application of Lean Production principals to construction processes. The construction industry, however, has rejected many ideas from manufacturing because of the belief that construction is different; construction has

unique and complex projects in highly uncertain environments under great time and schedule pressure (Howell, 1999). Although there is some truth to this statement, Howell and Ballard argue, "Manufacturing is a special case of construction because it alone is characterized by multiple copies of the same project".

2.3 Simulation Modeling

"Construction simulation is a powerful tool that can be used by a construction a company for a number of tasks such as productivity measurement, risk analysis, resource planning, design and analysis of construction methods, and site planning" (Sawhney et al. 1998). Computers allow practitioners to create construction simulation models that can be used for experimentation, design assistance, or process analysis.

Simulation models can be classified in terms of the algorithm used to process them. Three algorithms are generally used for construction simulation models (AbouRizk and Hajjar, 1998):

1. Discrete-event simulation algorithms. This type of algorithm uses "next event processing" of activities based on logical relationships between process components and availability of resources. Discrete-even simulation algorithms create models that are dynamic in nature.
2. Static simulation algorithms: Static simulation algorithms are driven by prescribed process flow, which is not dependent on time or interaction of resources.

3. Continuous, or time dependent algorithms. These algorithms are often represented with a system of equations or mathematical models and then solved for steady state performance using differentiation, integration or by approximation.

Discrete-event and static simulation algorithms are the most commonly used for construction simulation applications (Appleton, 2002). Discrete-event simulation views a model as a set of events and transitions. Entities represent the active elements of the model as they travel throughout the network and trigger transformations (Hajjar and AbouRizk, 2000). Discrete-event simulation is used to describe processes where relationships exist between activities or operations. According to Hajjar and AbouRizk, simulation modeling is made most effective, in terms of use within the construction industry, through specialization and customization of modeling, analysis and reporting components within the simulation system. This philosophy led the development of special purpose simulation (SPS) tools.

AbouRizk defines special purpose simulation "as a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications and reporting are completed in a format native to the domain itself." AbouRizk adds that "projects to be modeled should share similar production methods, resources, and underlying internal and external effects." The computer program

Simphony was developed under the Natural Science and Engineering Research Council (NSERC)/Alberta Construction Industry Research Chair Program in Construction Engineering Management, and is a simulation platform for building both general and special purpose simulation tools (Appleton, 2002). Simphony was "developed with the objective of providing a standard, consistent and intelligent environment for both the development as well as the utilization of construction SPS tools" (Hajjar and AbouRizk, 1999).

2.4 Simulation Modeling and Lean Construction

To date little work has been done with respect to the incorporation of lean production theory and computer simulation. Tommelein suggests that the reason for this is that current industry project management tools have an inability to describe the construction process at a level in which lean production can be studied.

Tommelein (1998) completed one of the first works on the incorporation of lean principles in computer simulation models. Pull techniques were incorporated into a pipe spool installation model and the results show how the overall process can be improved.

Tommelein et al. (1998) demonstrate a game called "The Parade Game". A hypothetical model is used to demonstrate how linked operations effect one another in construction processes. Lean concepts, buffers, and workflow reliability are demonstrated.

Al-Sudairi et al. (1999) reported on the effects that five lean principles had on a generic steel erection computer model. An overall improvement was noted, however the model became volatile and sensitive to variances in the process. It was determined that construction buffers are critical components for the implementation of lean principles.

2.5 Conclusions

This chapter provides an overview of lean production theory, computer simulation of construction activities, and the incorporation of lean principles in computer models.

Although lean production concepts have been accepted in manufacturing, they have generally been rejected in the construction industry. In recent years research has been dedicated to transferring the ideas of lean production to construction. Apart from the work completed by Tommelein (1997), Tommelein (1998) and Al-Sudairi et al. (1999) little work has been done to incorporate the concepts of lean production into computer simulation models. The work that has been completed focuses on the application of lean concepts to unique, stand-alone models; a framework for the generic implementation of lean concepts in any computer model has yet to be developed.

Chapter 3

Understanding Surface Works Operations in Road Construction

3.1 Background

The purpose of this chapter is to describe the processes involved in the surface works operations of road construction. Understanding these processes is a necessary first step in the development of a special purpose simulation tool.

The information described in this section was obtained through detailed activity studies in cooperation with the NSERC/Alberta Construction Industry Research Chair in Construction Engineering Management and Standard General Inc., and through discussions with industry practitioners (Standard General Inc.). The information was supplemented by process observations, and through the personal experiences of the author.

3.2 Surface Works Operations

Surface works operations of road construction can be grouped into three main categories:

1. Subgrade Operations
2. Aggregate Operations
3. Asphalt Operations

3.2.1 Subgrade Operations

As the name suggests, subgrade operations involve the preparation of subgrade to a specified degree in order to ensure an appropriate foundation for the aggregate and asphalt structures of a road. Depending on the condition of the original ground, there are several different processes that can occur. These processes can involve (but are not limited to) grading the clay to ensure proper elevation, drying or stabilizing the clay and re-compacting it to a specified density, or in extreme cases, excavating and replacing unsuitable material from the roadway. The soil conditions on a particular project dictate the amount and type of subgrade preparation required. In most cases a combination of several types of subgrade preparations are used on any given project. In addition to soil conditions, weather can have a significant influence on the subgrade operation. With respect to weather, the roadway is at its most vulnerable stage during the subgrade operation; rain can increase the amount of work required by saturating the soil with water, or in some cases undoing work that has already been completed.

Figure 3-1: Subgrade Operations (Cement Stabilization of Soil)

3.2.2 Aggregate Operations

Aggregate operations involve the supply and placement of aggregate to the construction site. Although the operation itself is more complicated than the subgrade in terms of its sub processes, its activities and their associated production values are less susceptible soil conditions and inclement weather. That being said, because aggregate placement occurs after subgrade preparation, the uncertainties associated with that process, directly affect it. For this reason, it is desirable for aggregate placement to follow closely behind subgrade preparation in order to "protect" it from poor weather. There are thee main sub processes that combine to govern the overall production rate of the aggregate operation; the aggregate pit, haul cycle, and on site placement. The resources required for this operation include a loader at the aggregate pit, aggregate haul trucks, site labour, a grader(s) to place the material, and packers to ensure that density requirements are met.

Figure 3-2: Aggregate Operations (Material Delivery and Dumping)

Figure 3-3: Aggregate Operations (Material Placement)

Aggregate trucks begin at the aggregate pit where they wait until a loader is available to load them. Once loaded, the trucks proceed on a haul road and arrive at the construction site. The trucks wait for site labour to direct them where to dump their load and once that is complete they proceed on a haul road back to the aggregate pit to begin the cycle again (Figure 3-4). The aggregate placement process runs in parallel to the haul cycle. The grader(s), and packer(s) wait for aggregate to be delivered to the site, and as it arrives it is continually placed, graded, and packed. It is important to note that aggregate is also required for the production of asphalt. For the purposes of this study the production of asphalt will include the delivery the aggregate required. In addition, it is assumed that crushing operations are performed as required to meet the demand of the aggregate operation.

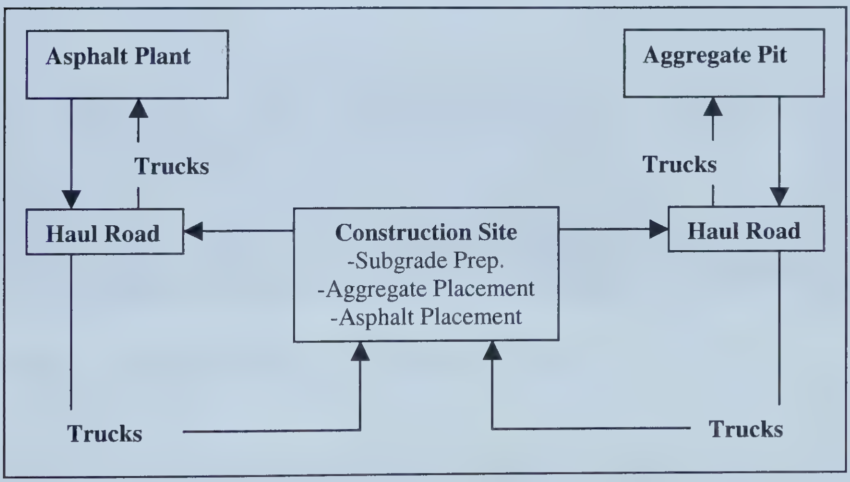

Figure 3-4: Aggregate and Asphalt Haul Cycle

3.2.3 Asphalt Operations

Asphalt operations involve the production, supply and placement of asphalt to the construction site. This operation is similar in complexity to the aggregate operation, however there are some key differences at the sub process level.

As with the aggregate operation, there are three main sub processes that combine to govern the overall production rate; the asphalt plant, haul roads, and on site placement. The resources required for this operation include the asphalt plant, asphalt haul trucks, the asphalt paver(s), and packer(s).

Figure 3-5: Asphalt Operations (Tandem Asphalt Paving)

Asphalt trucks begin at the asphalt plant where they are loaded and weighed in the order at which they arrive. Although the asphalt plant usually begins the cycle with an amount of asphalt in inventory, it must continually produce asphalt in order to meet the demand of the trucks it is loading. The trucks proceed on a haul road and arrive at the construction site. The asphalt paver can only place one load at a time so when the paver becomes

available, a truck attaches to the paver and dumps its load at a rate dictated by the paver. Once this is complete the truck detaches from the paver, and proceeds on a haul road back to the asphalt plant to begin the cycle again (Figure 3-4). As mentioned previously, the aggregate required for the asphalt operation is assumed to be delivered to the plant as required.

3.3 Building a Typical Road Section

The three operations descried in the previous section follow one another and complete sections of road in a repetitive pattern. Figure 3-6 depicts a plan and side view of a typical road section. Upon examination of the cross section in Figure 3-6, it is evident that subgrade preparation must occur before aggregate placement, and aggregate placement must occur before asphalt placement.

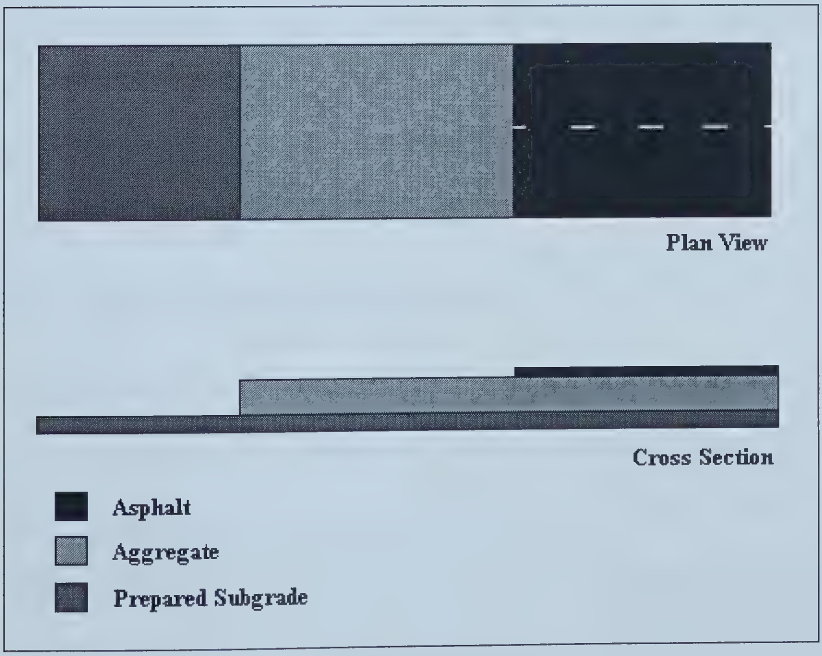

Figure 3-6: Typical Road Section

Road construction is performed as a continuous process, that is, the three operations occur at the same time. It would not be cost effective or practical, for example, to finish all of the subgrade on a road before aggregate placement began. For this reason the three operations are spaced out from one another; first subgrade, then aggregate, and finally asphalt.

Each operation consists of several activities that interact to generate an overall production rate. The production rates of each operation, in terms of square metres of road completed per hour, are often quite different from one another. Such things as road geometry, road structure, the length of the haul cycles, or by the number of trucks each operation uses to haul material can impact them. For this reason, the operations are spaced to minimize the effect using construction buffers. Typically a certain amount of aggregate, for example, would be placed before the asphalt operation begins. Once started, asphalt placement will commence until either the road is complete or the gap between the aggregate and asphalt operations has been closed (in other words there is not enough aggregate placed to continue). Asphalt placement will then stop until there is enough aggregate placed for it to start again.

3.4 Continuous Construction Processes

Varying production rates always pose a problem for construction projects that involve activities with linear relationships. Linear relationships between construction activities are those that apply to continuous operations as described above. A continuous activity occurs throughout the duration of a project in a continuous fashion. Linked continuous activities are said to have linear relationships. Figure 3-7 depicts a velocity diagram of an

example construction project with three activities with such relationships. A velocity diagram is a plot of the cumulative production quantity versus time for a particular activity. In the case of the example, Activity 1 is a predecessor for Activity 2, which is predecessor for Activity 3 (each having a linear relationship with the other).

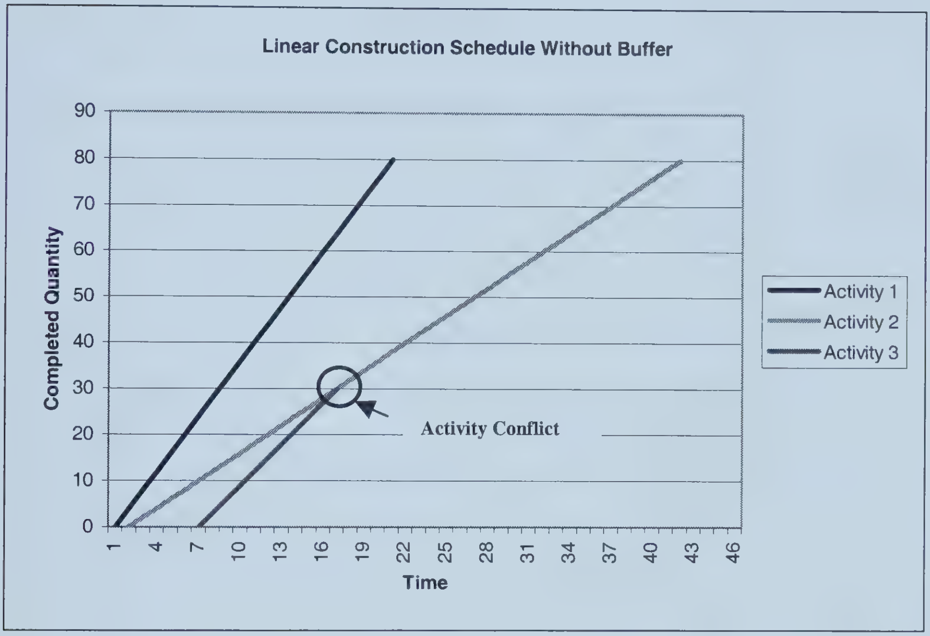

Figure 3-7: Linear Construction Schedule with Activity Conflict

Activity 1 begins first and progresses at a certain rate. Once Activity 1 has started, Activity 2 can begin. At any given time Activity 1 must have more completed quantity than Activity 2 because of their linear relationship. When this is not the case, at time 18 for example, an activity conflict occurs; Activity 3 has a greater production rate than Activity 2, and therefore it "catches up" with it's completed quantity. In these types of projects practitioners can either increase/decrease production rates, or introduce construction buffers to ensure that linked activities do not interfere with one another.

Figure 3-8 shows an example of a buffer size that might be used to ensure that an activity conflict does not occur.

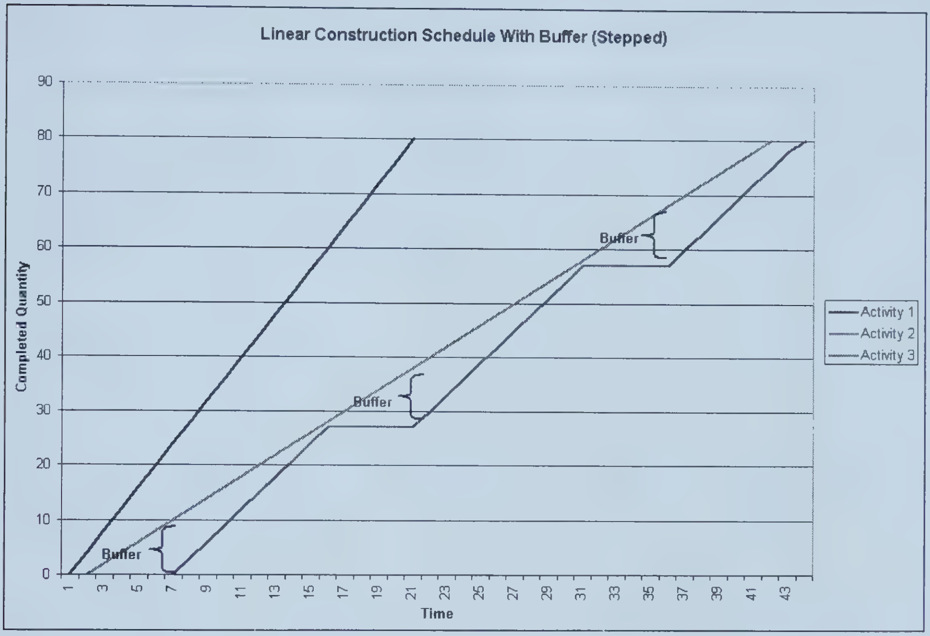

Figure 3-8: Linear Construction Schedule with Several Buffers

In Figure 3-8, Activity 3 is started after a specific quantity is completed by Activity 2 (construction buffer). Once Activity 2 no longer has a greater completed quantity, Activity 3 stops until the construction buffer is satisfied. Construction buffers can be large or small, depending on the particulars of the project. For example, one could use a large buffer between Activities 2 and 3 at the start of the project. This would allow Activity 2 to complete enough quantity ahead of Activity 3 to ensure that Activity 3 never "catches up" (is not stopped).

In the case of the subgrade operation in road construction operations, it becomes risky for a contractor to work too far ahead of the aggregate operation because poor weather can damage completed subgrade; this can have serious consequences in terms of schedule and budget. It, therefore, becomes necessary to have a smaller construction buffer (like in Figure 3-8) between these types of activities. Contractors must balance between optimizing the utilization of resources, protecting work that has been completed and keeping other contractual obligations.

3.5 Conclusions

The purpose of this chapter is to describe the processes involved for the surface works operations of road construction, which are key in the development of a special purpose simulation tool. The most important concept that arises from this chapter is the fact that each of the three operations described are linked with a linear relationship. Construction companies space out the operations with "buffers" to account for the differing production rates that each operation has. The subgrade, aggregate and asphalt operations are then able to continue with less influence on one another's processes.

Chapter 4

Development of the Surface Works Road Construction Template

4.1 Introduction

This chapter serves two important purposes: 1) to extract logical relationships from the actual road construction processes for the purpose of establishing guidelines for which a SPS template can be created; and 2) to use these guidelines to develop the Surface Works Road Construction (SWRC) SPS Template that will enable users to create computer simulation models of surface works operations of road construction.

It is important to recognize the difference between a special purpose simulation template and a simulation model. A SPS template is made up of simulation elements that are programmed using detailed code and are meant to perform specific functions. A simulation model is a collection of these elements arranged in a specific way with unique input parameters. A SPS template can be used to create a variety of simulation models that can represent numerous construction project configurations.

4.2 Process Relationships and SPS Template Requirements

The SWRC Template was developed using the flow chart depicted in Figure 4-1. It shows the main processes of surface works road construction and how they interact. The flow chart was created by simplifying the overall process that was described in Chapter 3. This simplification was only possible after a detailed analysis of the operation was

performed. Only then could it be determined which sub-processes could be ignored and which had to be focused upon.

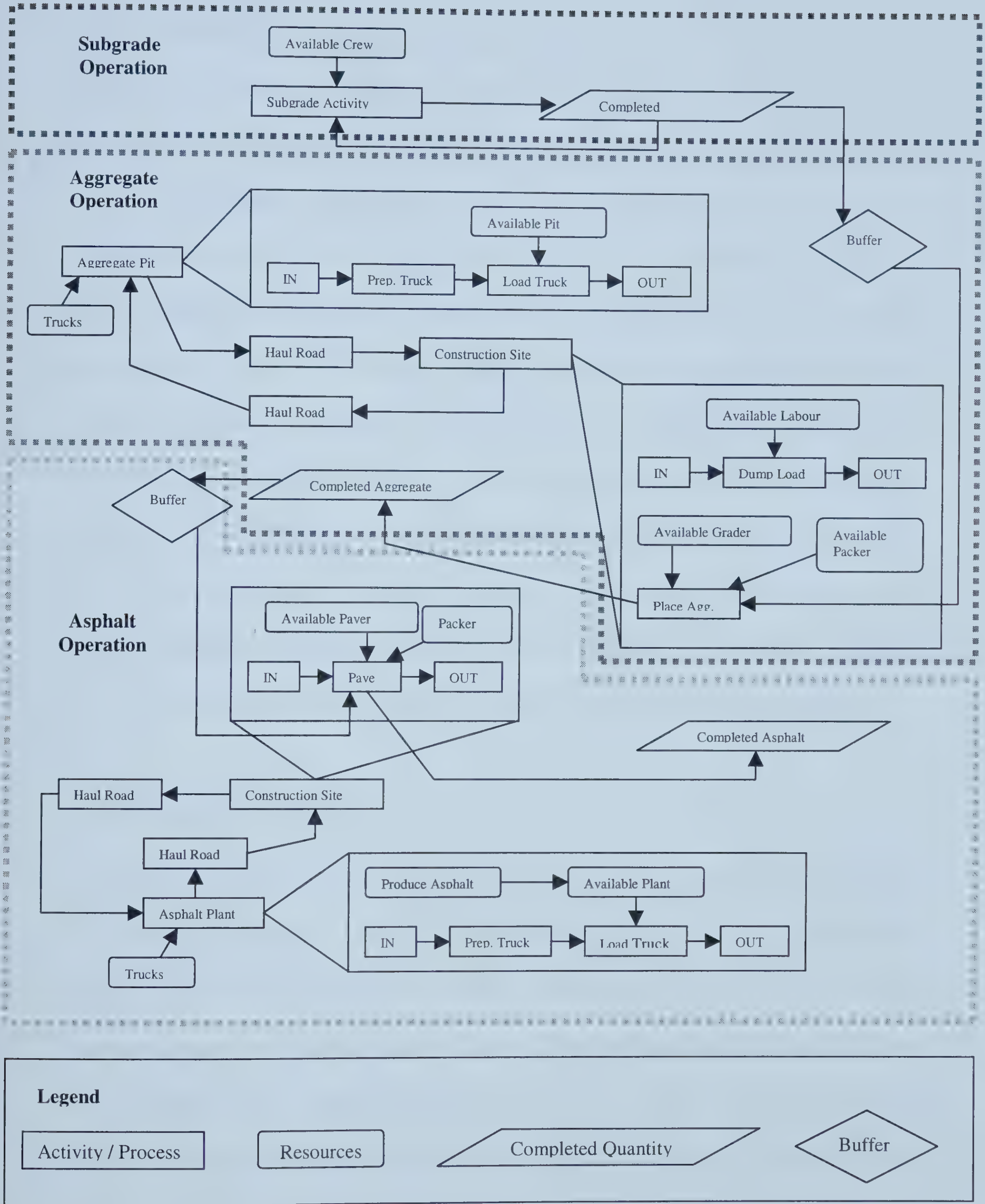

Figure 4-1: Surface Works Operations Process Flow Chart

4.2.1 Subgrade Operations

In the development of the subgrade operations portion of the SWRC Template it is important to understand the degree of complexity that is required. When the subgrade operation is performed the main uncertainties that exist are the soil conditions and weather. The subgrade operation is the first activity on any road construction project (surface works), it affects both the aggregate and asphalt operations. Overall the subgrade production rate is less uncertain than both the aggregate and asphalt operations, and therefore it is not the focus of the SWRC Template, but is included as a necessary component of the entire operation. Future developments of the SWRC Template could be done to incorporate the effects that weather and soil conditions have on the subgrade operation. For simplifications in this research, subgrade operations can be represented by one activity whose production rate is variable depending on the impacts of such things as the type of subgrade preparation, soil conditions, and weather. For the SWRC Template, the user will use professional judgment and experience to input this production rate.

4.2.2 Aggregate Operations

As with the subgrade operation the development of the aggregate operation for the SWRC Template requires some simplification from the actual process. The aggregate operation can therefore be grouped into three main sub-processes; loading aggregate, hauling aggregate, and placing aggregate. Each of these sub-processes is shown in Figure 4-1. One aspect of the operation in Figure 4-1 to take note of is the buffer that is placed between the completed subgrade and aggregate placement activity. This buffer is set to a

specified value and ensures that a certain amount of subgrade remains completed ahead of the aggregate operation, as discussed in Section 3.4.

4.2.3 Asphalt Operations

As with the aggregate operation, the asphalt operation can be grouped into three main sub-processes; asphalt production and loading, asphalt hauling, and asphalt placement. Figure 4-1 depicts the asphalt operations sub-processes. One difference between the aggregate and asphalt operations is that the asphalt haul trucks require the paver resource in order to dump their load. In the aggregate operation the trucks arrive on site and only require site labour and not the grader to dump their load. This is an important difference, because the grader resource is able to place aggregate that is stockpiled on site, while the paver resource must wait for material and place it as it arrives. A buffer between the aggregate and asphalt operations is used to ensure that a certain amount of aggregate remains completed ahead of the asphalt operation.

4.3 SWRC Template Description

The template is comprised of the three main processes that make up surface works in road construction: Subgrade Operations, Aggregate Operations, and Asphalt Operations. The simulation begins with the subgrade operation. Once the Subgrade-Aggregate buffer has been reached, the Aggregate operation is allowed to begin. If at any time the aggregate quantity that is placed exceeds the Subgrade-Aggregate buffer the aggregate operation is halted until the buffer is restored. Once the Aggregate-Asphalt buffer has been reached, the Asphalt operation is allowed to begin. The same rules apply to this

buffer as to the Subgrade-Aggregate buffer. The model proceeds in this cyclic fashion until the road construction is complete.

Once a simulation model has been run, the SWRC Template produces several statistical outputs that include the following:

1. Operational Production Rates. For each operation (Subgrade, Aggregate, Asphalt) statistical data is collected during the course of the simulation on hourly production. This information is displayed both numerically and graphically.

2. Resource Utilization. For each resource in the model statistical data is collected for both utilization and queue waiting times. This information is displayed both numerically and graphically.
3. Cycle Times. The material haul cycle (aggregate and asphalt) plays a significant role in the overall model. Truck cycle time data is collected during the model and is displayed both numerically and graphically.
4. Miscellaneous: Other outputs produced by the template include operational durations, overall project duration, measured throughput (overall), and cumulative quantity tracking,

Using these simulation outputs the user can perform various analytical functions including model sensitivity analysis, scenario analysis, and lean construction theory analysis. Sensitivity analysis allows users to change various input parameters and

measure the impact on the model. This enables practitioners to determine which activities are critical and require the most attention. Scenario analysis allows a user to model several different situations, and compare the output. For example, one could use the model to decide how many haul trucks to use by modeling several different scenarios and choosing the best result. Finally, the concepts of lean construction can be applied to a computer simulation. An approach for the systematic application of lean concepts to simulation is developed and described in detail in Chapters 6, and is one of the main goals for the development of this template.

4.4 SWRC Template Modeling Elements

The following section describes the main user elements required to create a model with the SPS template. The template was developed using Simphony; it is intended for use by industry practitioners, and therefore is designed in such a way to ensure user flexibility and user friendliness (the user need not have a simulation or programming background). The main elements (described below) were programmed using Simphony's "common template". The common template elements are used as "child elements" of the SWRC Template elements. Common template child elements provide a computer programmer/simulator with elements that have been preprogrammed to perform generalized tasks; combining and editing several common template elements together helped to create the bulk of the SWRC Template. This method of computer simulation, allows the model to be easily used by the average practitioner while ensuring it is flexible enough that an individual familiar with computer simulation or computer programming can make specific changes to simulation events or processes at a more detailed level

(Mohamed and AbouRizk, 2001). The following sections describe how each of the SWRC Template elements was created using Simphony's common elements. For additional information on the element parameters and statistical outputs, refer the SWRC Template User Manual, which is located in Appendix A.

4.4.1 Surface Works Road Construction Parent

The Surface Works Road Construction Parent element, shown in Figure 4-2, is a container for the model. It serves only this purpose, however a model cannot be created unless it is within this element. All elements of the model are child elements of the SWRC Parent Element.

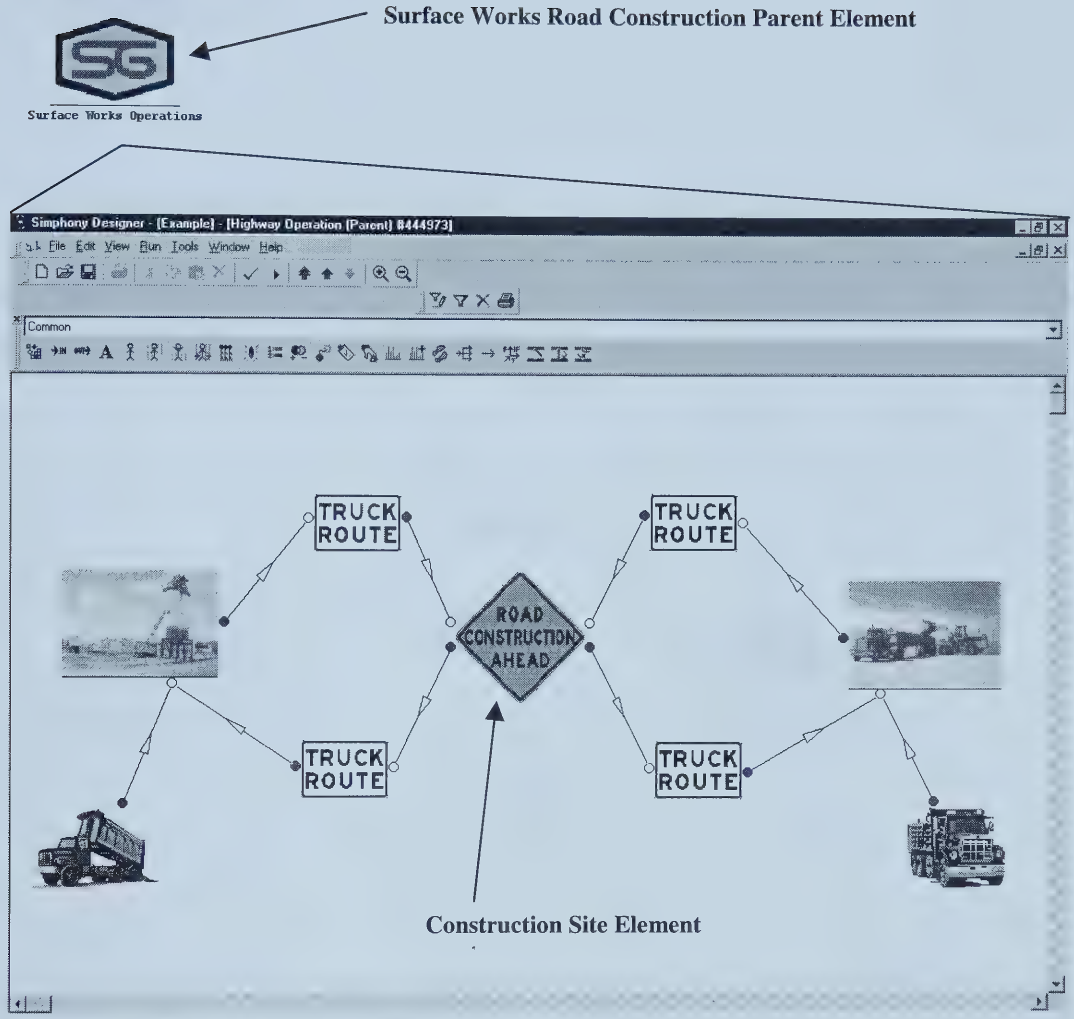

Figure 4-2: SWRC Example Model

4.4.2 Construction Site

The Construction Site Element, shown in Figures 4-2 and 4-3, is the heart of the SWRC Template. The Construction Site's child elements (Figure 4-3) are the three operations of surface works road construction (Subgrade, Aggregate, and Asphalt).

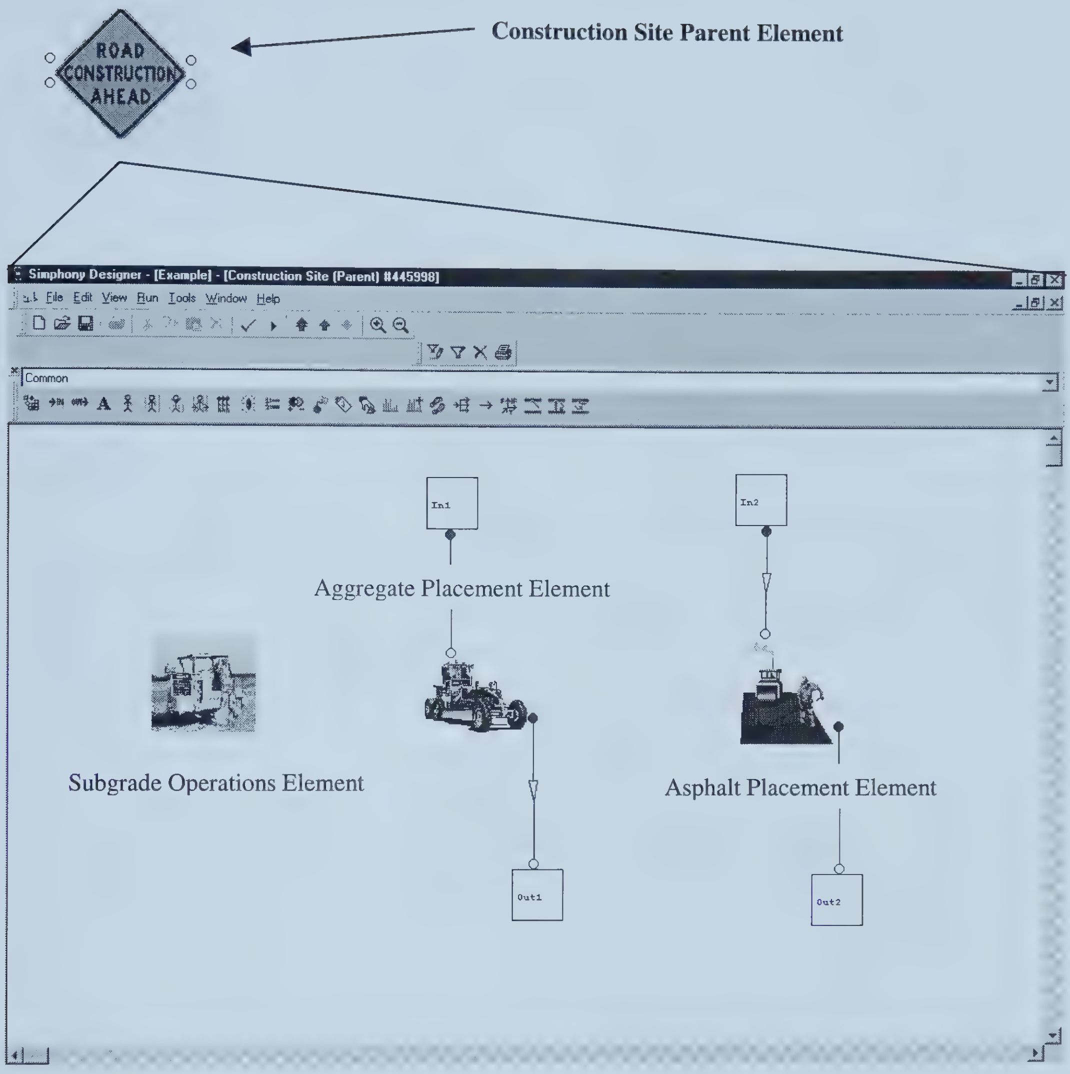

Figure 4-3: Construction Site Child Elements

4.4.3 Sub-grade Operation Child Element

The Subgrade Operation Element represents the subgrade operation. Figure 4-4 displays the child common elements that were used to create it. The element is driven by a single entity, which cycles through the common elements until the subgrade operation is complete.

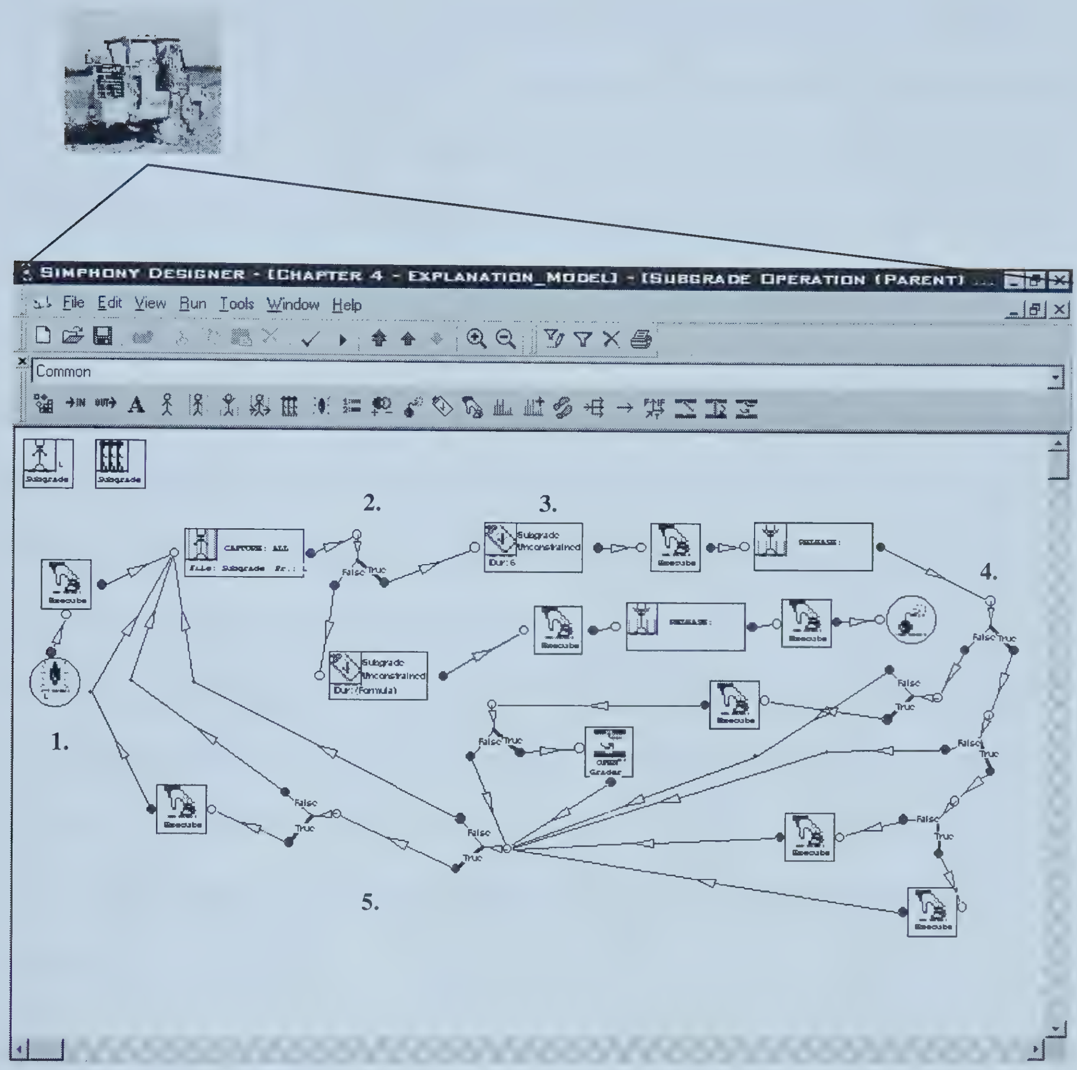

Figure 4-4: Subgrade Operation Element Common Elements

The entity is created at Location #1 (Figure 4-4) when the simulation begins. From there it captures the subgrade resource, which is used to represent the crew performing the work. At Location #2, the entity reaches a conditional branching element, which is used to split the path of the entity; if the subgrade operation is not complete the entity proceeds to Location #3 where the subgrade preparation activity is represented. The duration of

this activity is set at 6 minutes, and the amount of subgrade completed in this time is dependent on the user defined production rate entered for the element. Once the duration has been completed the entity proceeds to Location #4; this group of conditional branching elements is responsible for directing the entity depending on whether or not the aggregate operations within the model should be started or stopped. This is accomplished by checking the subgrade and aggregate that has been completed and comparing them against the user defined buffer that has been entered for the operation. The conditional branching element at Location #5 splits the path of the entity to ensure that the asphalt operation within the model is stopped if the buffer between it and the aggregate operations is reached (this can become necessary if an operational interference occurs while the aggregate operations are stopped and the asphalt operations are not). The entity repeats this cycle until the subgrade is complete, at which time the conditional branching element at Location #3 directs it off it's path to be destroyed. Before this occurs the entity passes through an execute element that ensures that the aggregate operation is started.

4.4.4 Aggregate Placement Child Element

The Aggregate Placement Element represents the aggregate placement activities within the model. Figure 4-5 displays the child common elements that were used to create it. There are 2 sub-processes that occur within the aggregate placement element; 1. Aggregate delivery by haul truck entities, and 2. Aggregate placing and compaction. In the first process, aggregate haul trucks are represented by individual entities that "travel" through the various modeling elements. Haul truck entities enter the element at Location

#1, and immediately enter a group of conditional branching elements, that determine whether or not enough aggregate has been delivered to the site. If sufficient aggregate has been delivered to complete the road section, the aggregate trucks are diverted and destroyed.

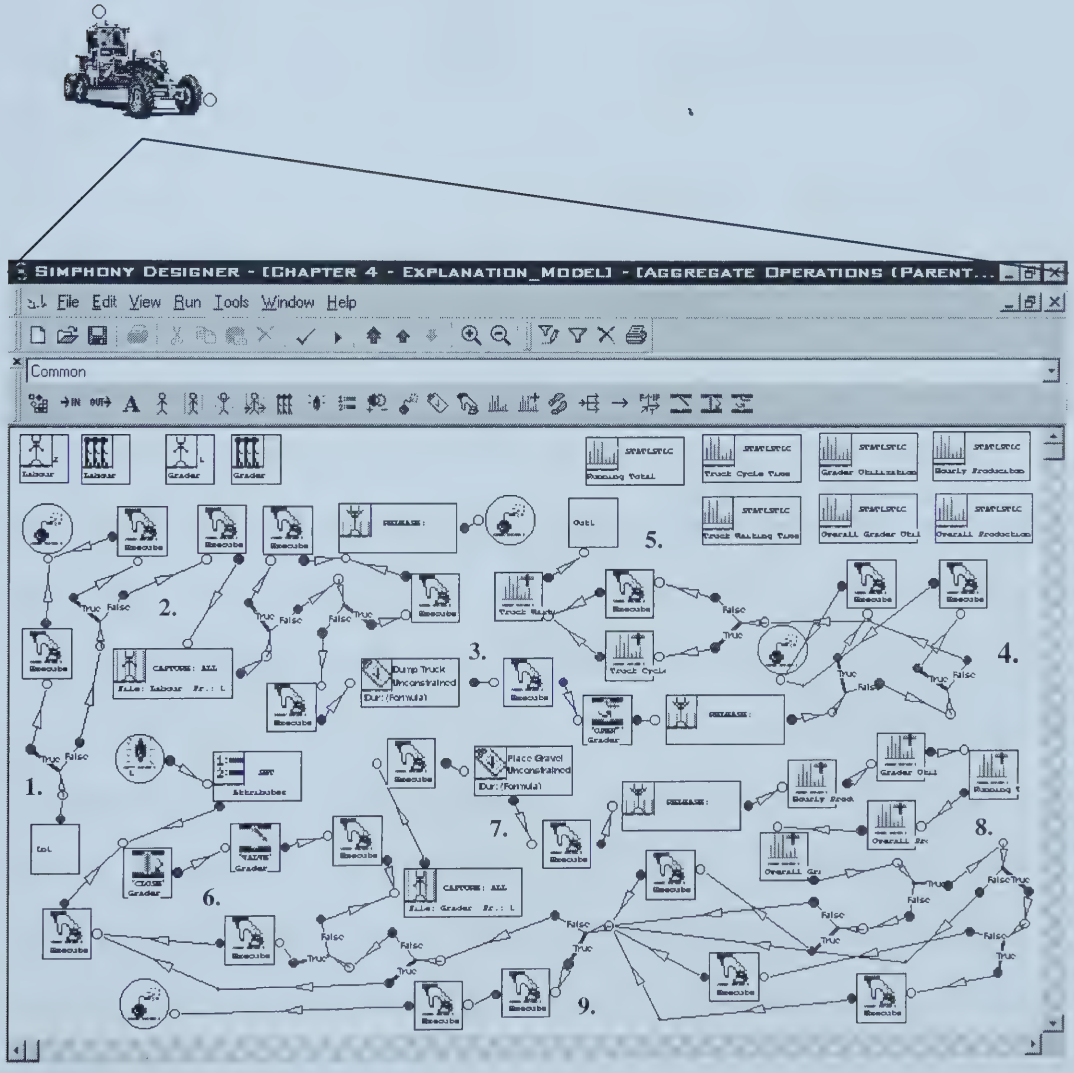

Figure 4-5: Aggregate Placement Common Elements

If sufficient aggregate has not been delivered, the aggregate haul trucks proceed to Location #3, where they dump their load; the duration of this activity is determined through a user defined input in the element parameters. When the haul truck entities are finished dumping their load, they continue to another group of conditional branching elements that perform the same function as the first set. If it is determined that more aggregate is required, the haul truck entities exit the Aggregate Placement Element and proceed back to the Aggregate Pit Element, where they will be loaded for their return back to the construction site.

The second process runs in parallel with the first and involves the placement of the aggregate that is delivered to the site. A single entity is created when the simulation begins and is used to drive this process. The entity is kept in a valve (Location #6), where it waits until material is delivered to the site. The valve is opened by the haul truck elements after they dump their load. Once released, the entity captures a resource used to represent the grader(s) and proceeds to Location #7 where it places the aggregate that has been delivered and stockpiled on the construction site; this occurs at a rate that is defined by the user in the element parameters. While this is occurring, haul truck entities continue to arrive on site and dump/stockpile aggregate that is to be placed. Once complete the entity registers several statistics and proceeds to the conditional branching elements at Location #8. These elements are responsible for directing the entity depending on whether or not the asphalt operations within the model should be started or stopped. This is accomplished by checking the aggregate and asphalt that has been completed and comparing them against the user defined buffer that has been entered for

the operation. The conditional branching element at Location #9 determines whether or not the aggregate placement activity is complete, and if so directs the entity so that it may be destroyed. Before it is destroyed it enters an execute element that ensures that the asphalt operation has been started.

4.4.5 Asphalt Placement Child Element

The Asphalt Placement Element represents the asphalt placement activities within the model. Figure 4-6 displays the child common elements that were used to create it. As with the aggregate operation, asphalt haul trucks are used as entities that "travel" to and from the various modeling elements. Haul truck entities enter the Asphalt Placement Element at Location #1, and are directed by a set of conditional branching elements that determine whether or not enough asphalt has been delivered to the site. If they are allowed to continue they wait in a queue, at Location #2, until the paver resource becomes available (only one truck may attach to the paver to dump it's load at any given time). Once this occurs a haul truck captures the paver, positions onto it, and dumps its load (Locations #3 and #4). The durations of these activities are determined through user-defined parameters of the element. The asphalt truck entity then releases the paver (Location #5), registers several statistics, and exits the element. Conditional branching elements are used to determine whether the haul truck entities are required to deliver more asphalt or if they can be destroyed.

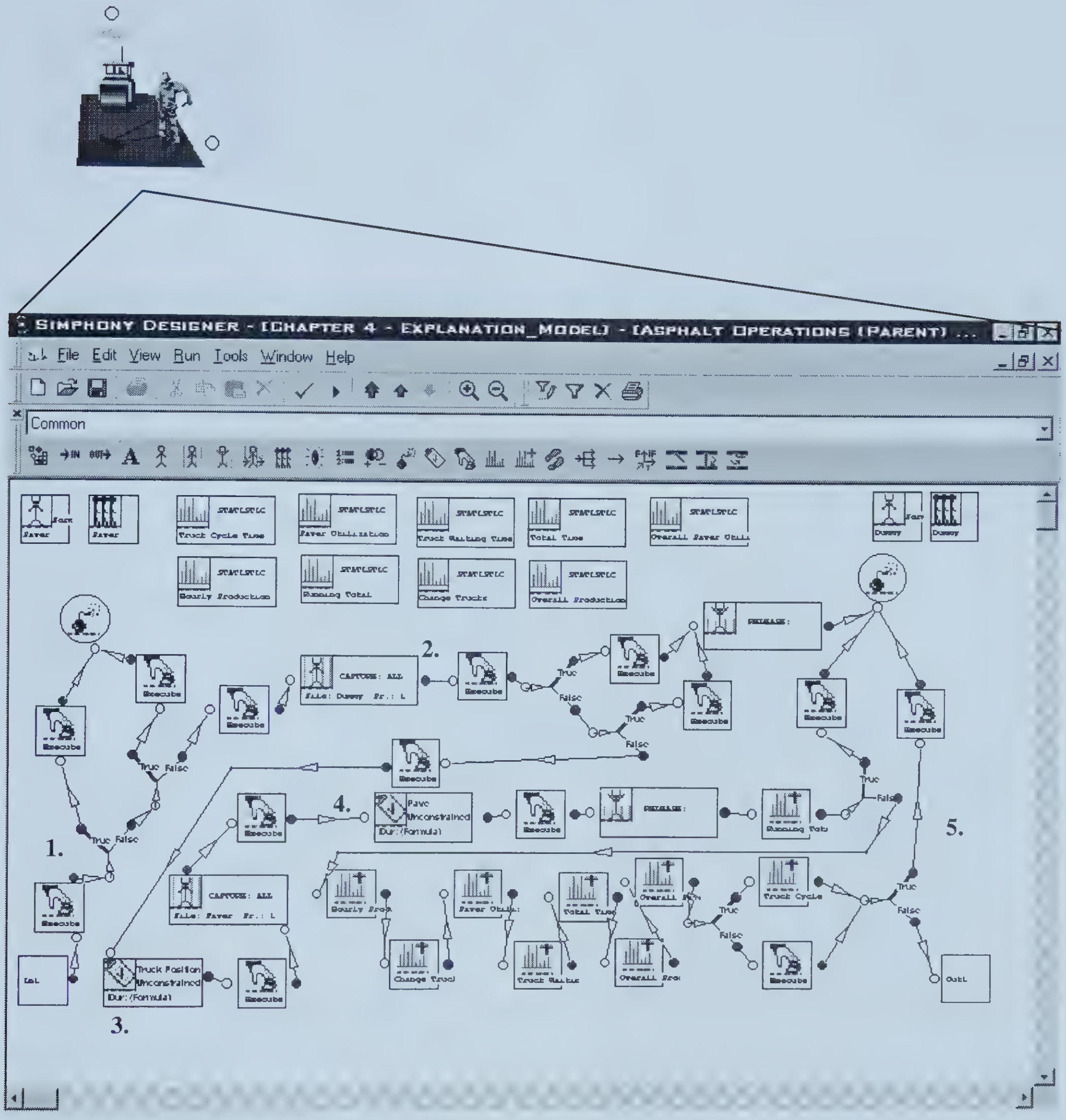

Figure 4-6: Asphalt Placement Common Elements

4.4.6 Asphalt Plant Element

The Asphalt Plant Element represents the asphalt production activities within the model. Figure 4-7 displays the child common elements that were used to create it.

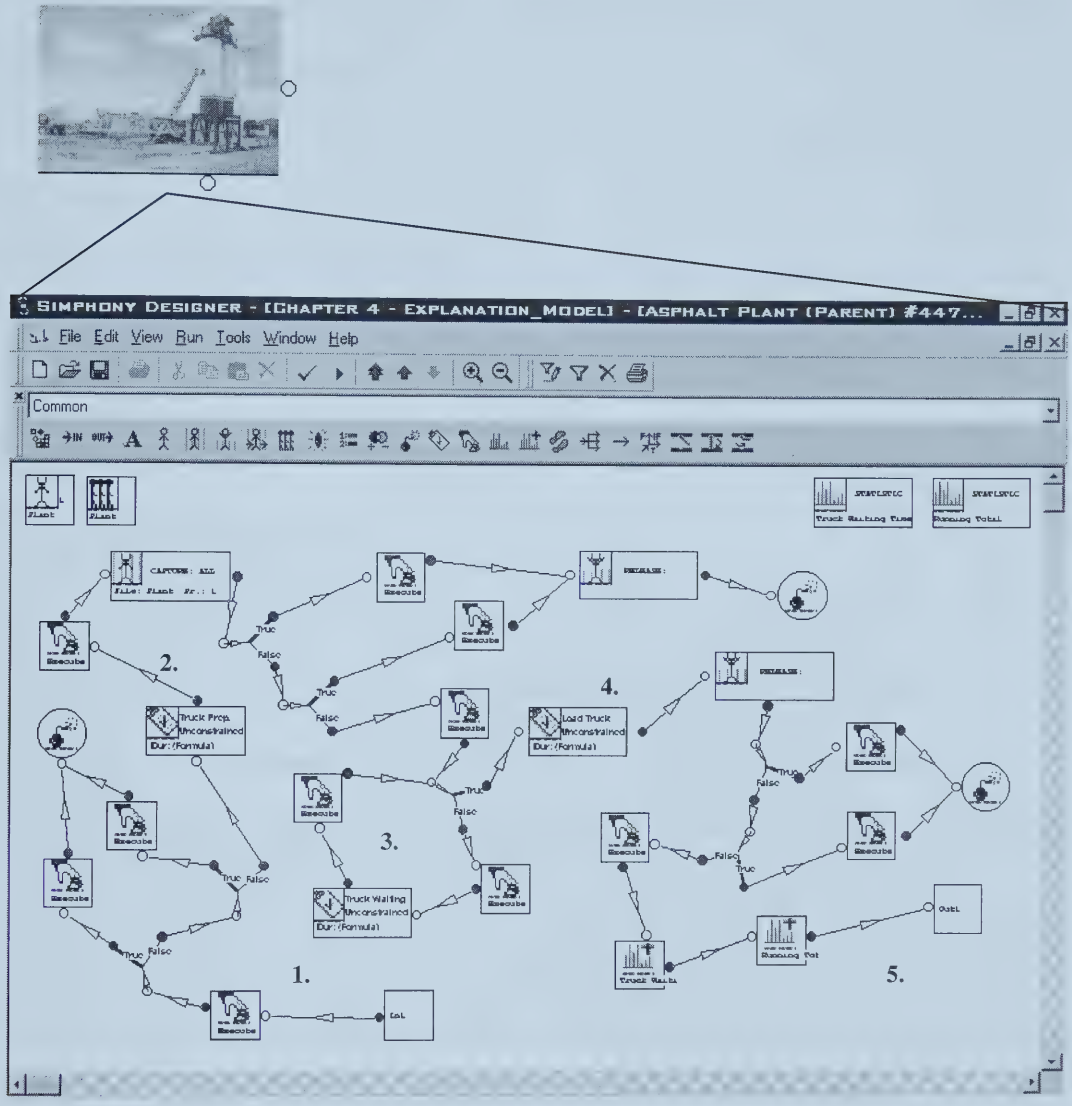

Figure 4-7: Asphalt Plant Common Elements

Asphalt haul truck entities enter the Asphalt Plant Element at Location #1, and are directed by a set of conditional branching elements that determine whether or not enough asphalt has been delivered to the construction site. If the trucks are allowed to continue they arrive at the Truck Preparation activity (Location #2), the duration of which is defined by an element user input parameter. Once complete, the trucks wait in a queue

for the asphalt plant resource to become available to load them (one at a time) at Location #3. If there is not enough asphalt in storage, the truck is routed into a waiting activity by a conditional branching element. A truck is then loaded by the plant at Location #4, and is checked by a set of conditional branching elements once again to determine whether enough asphalt has been delivered to the site. If more is needed, the truck registers several statistics, and exits the Asphalt Plant Element to proceed to the construction site at Location #5.

4.4.7 Aggregate Pit Element

The Aggregate Pit Element represents the aggregate production activities within the model. Figure 4-8 displays the child common elements that were used to create it. Aggregate haul truck entities enter the Aggregate Pit Element at Location #1, and are directed by a set of conditional branching elements that determine whether or not enough aggregate has been delivered to the construction site. If the trucks are allowed to continue they arrive at the Truck Preparation activity (Location #2), the duration of which is defined by an element user input parameter. Once complete, the trucks wait in a queue for the loader resource to become available to load them (one at a time) at Location #3. A truck is then loaded and is checked by a set of conditional branching elements once again to determine whether enough aggregate has been delivered to the site. If more is needed (checked during the simulation), the truck exits the Aggregate Pit Element and proceeds to the construction site at Location #4.

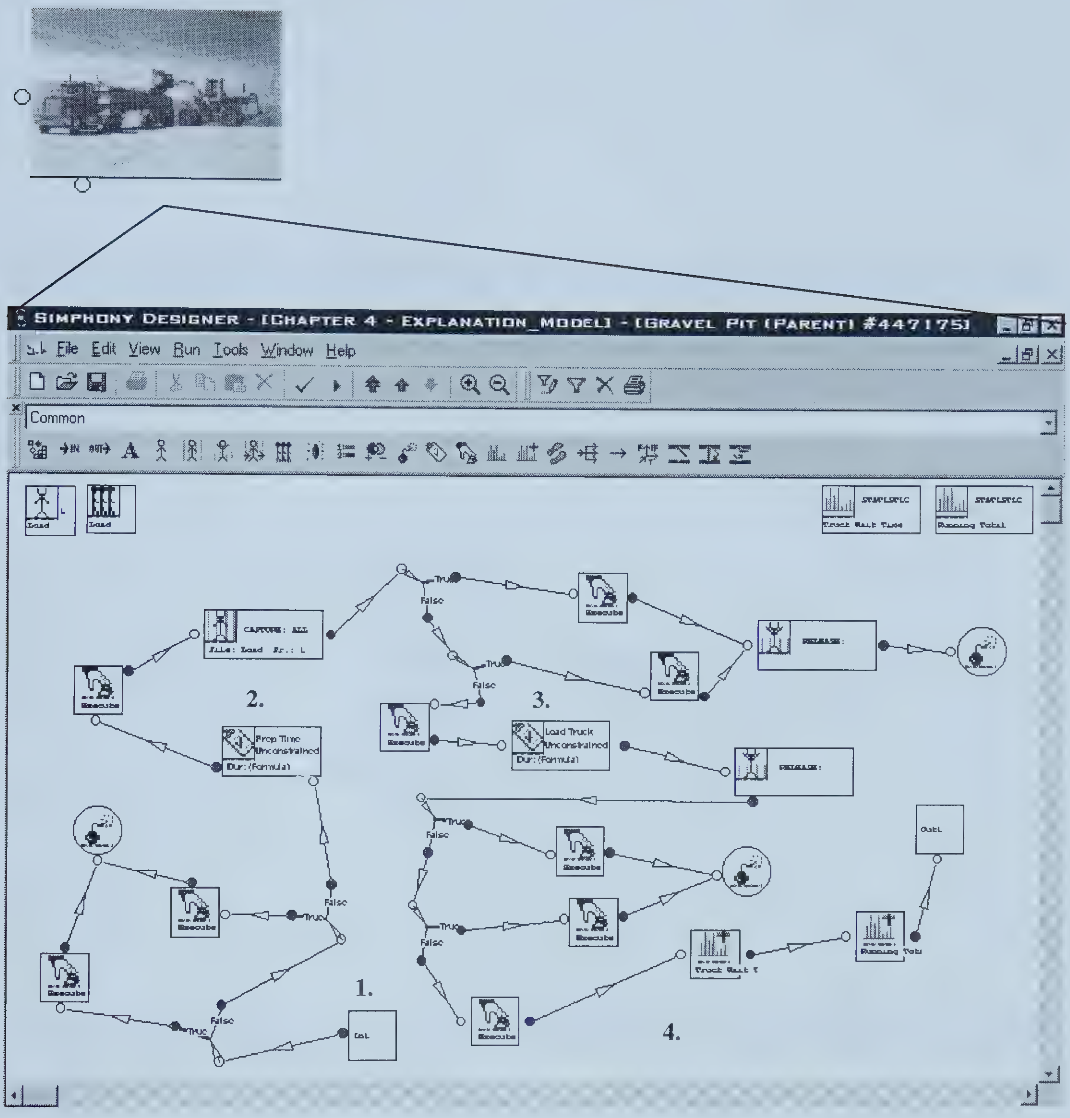

Figure 4-8: Aggregate Pit Common Elements

4.4.8 Haul Road Element

The Haul Road Element represents the material delivery activities within the model. Figure 4-9 displays the child common elements that were used to create it. Haul truck entities (both asphalt and aggregate) enter the element at Location #1.

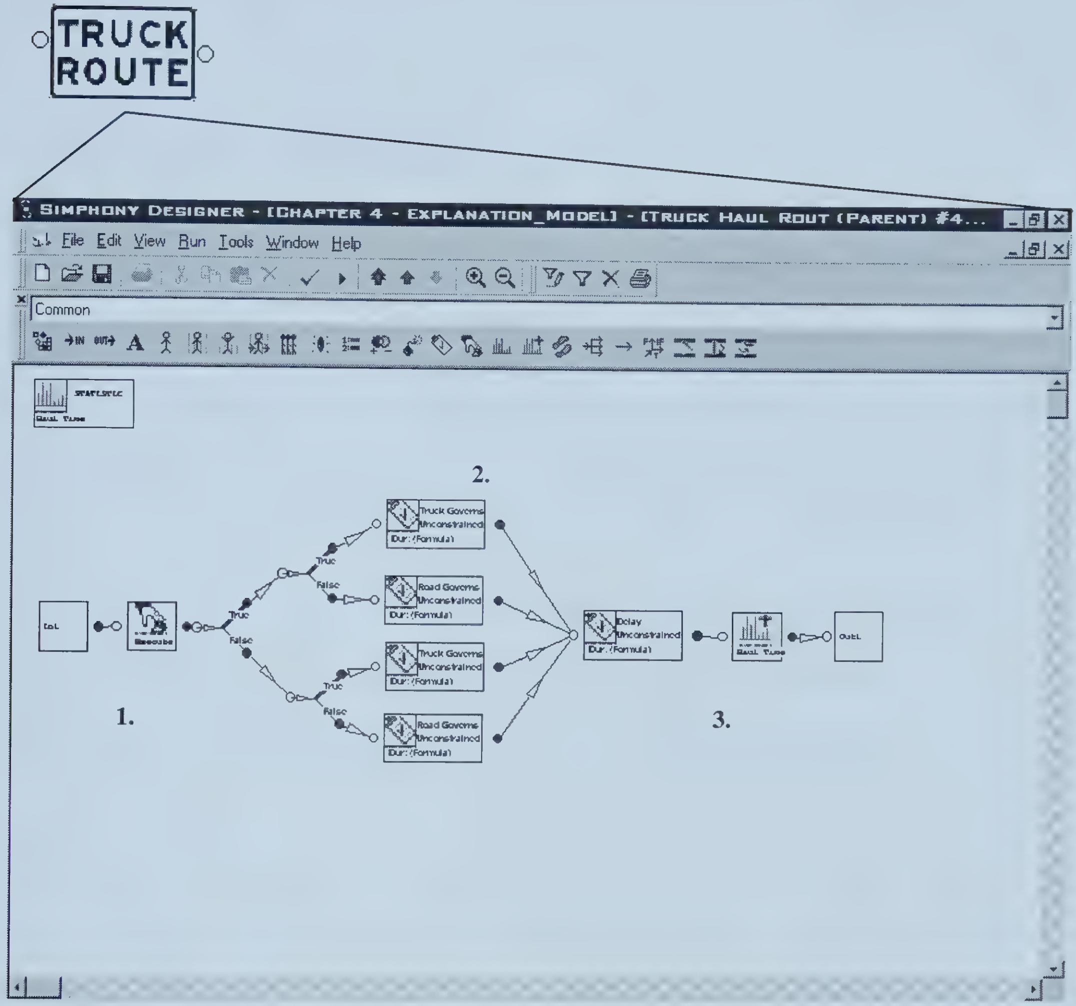

Figure 4-9: Haul Road Common Elements

They proceed to a set of conditional branching elements that determine which speed the truck entity will proceed at. Haul speeds depend on user inputs for both the haul truck and haul road elements. The duration of the trip is calculated by using the appropriate haul speed, and haul distance (a user defined parameter of the element). The haul trucks then reach the delay activity (Location #3), which holds them for an amount of time

determined by a user-defined parameter. This is meant to simulation delays such as traffic lights etc. on the haul road.

4.4.9 Aggregate / Asphalt Truck Elements

The Haul Truck Elements represent the aggregate and asphalt haul trucks within the model. Figure 4-10 displays the child common elements that were used to create them. As stated in the previous sections the aggregate and asphalt haul trucks are represented as individual entities within the model. When the respective operation begins (aggregate or asphalt), a number of truck entities is created (Location #1) depending on the user defined parameter for this element. Each truck is assigned several attributes, such as Speed, Capacity, etc. at Location #2. The trucks leave the Aggregate/Asphalt Truck Element and proceed to the Aggregate Pit or Asphalt Plant at Location #3.

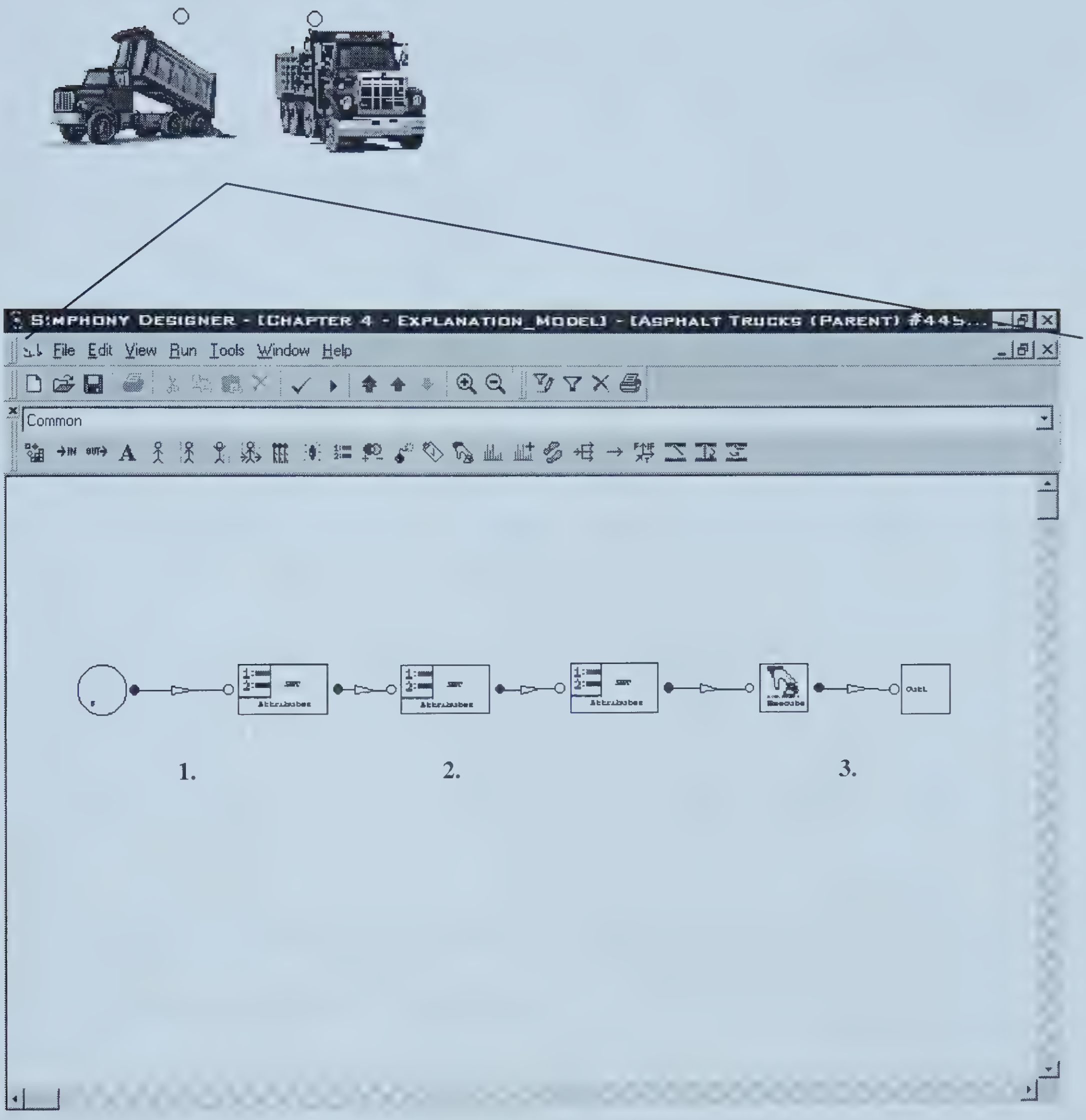

Figure 4-10: Asphalt/Aggregate Haul Truck Common Elements

4.5 Future Developments and Enhancements

The following describes various future developments that could be preformed in order to enhance the proposed SWRC Template.

- In its current form, the SWRC Template has one input for the total area of the road that is to be models. The Subgrade, Aggregate, and Asphalt Operations use this area as each of their individual quantities. This assumes that the amount of subgrade preparation, for example, is equal to the amount of aggregate, which may or may not be the case. Future developments may include separate inputs for each of these operations.
- Because the SWRC Template is designed to model one road construction project, that Asphalt Plant Element is only required to service one project at a time. In reality, an asphalt plant may be required to produce for several projects during the course of a particular day. Future enhancements to the template could make allowances for increased demand on asphalt production.
- The SWRC Template models the construction process continuously (24hrs per day, 7 days per week). In order to more closely reflect the actual process, enhancements could be made to include daily work stoppages, and breaks. This could take into account learning curve and process synchronization effects.
- Currently the SWRC Template does not take into account the randomness of equipment breakdowns or weather delays. Future research into the frequency of such events could enable them to be modeled within a simulation.
- The SWRC Template does not take into account quality control issues in its current state. During compaction of subgrade, aggregate layers and asphalt quality control is very important. This could be incorporated in future enhancements.

4.6 Conclusions

The chapter describes the development of the SWRC Template for use in creating simulation models for surface works operations of road construction. It is comprised of the three main processes: Subgrade Operations, Aggregate Operations, and Asphalt Operations. Each element within the template requires several input parameters that are dependent on several factors including the road structure, resource productivities, buffer sizes, and operational constraints. To create a model using the template, the user must select the appropriate elements from Simphony's User Element display, and arrange them in a similar fashion as in Figure 4-2. Once the elements are connected and their parameters entered, the model can be run. It was important to make the SWRC Template easy to use; flexible models can be created that are complex enough to accurately model surface works road construction operations, but simple enough to allow use by industry practitioners that have little or no knowledge of computer simulation techniques.

Chapter 5

Validation of The SWRC Template

5.1 Background

Anthony Henday Drive is part of the City of Edmonton's and the Province of Alberta's transportation and utility plan as an important link in the provincial North-South Trade Corridor. This long-term project is comprised of several four lane divided sections that will help reduce the growing traffic in Edmonton, particularly on Whitemud Drive. Prior to the start of The Anthony Henday Drive Extension Project (2000), two other sections of the road had been built. Figure 5-1 shows the overall plan for Anthony Henday Drive.

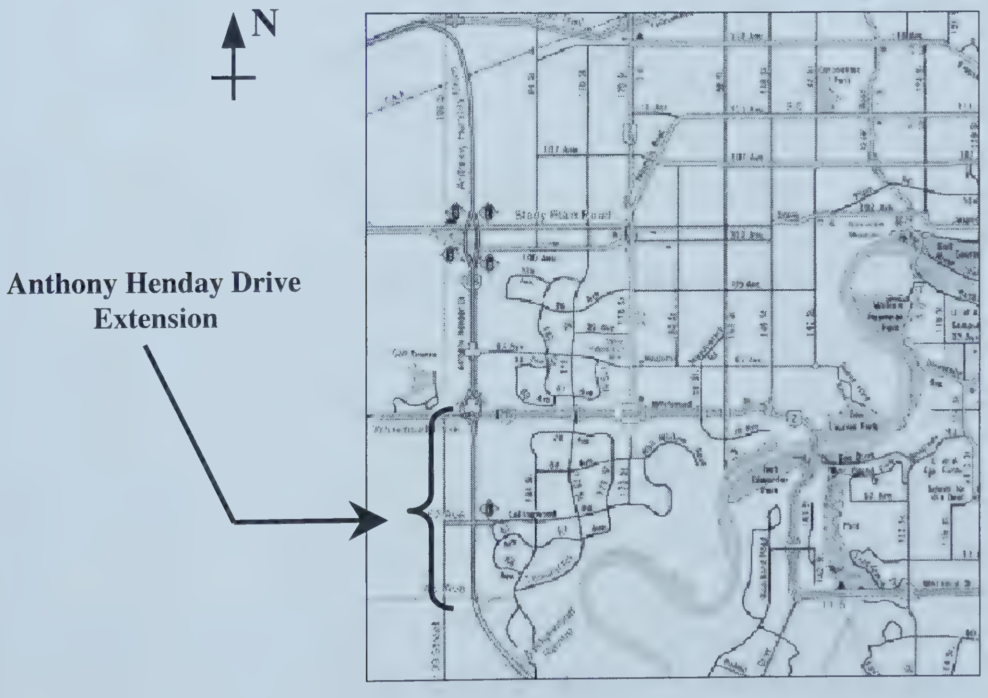

Figure 5-1: Anthony Henday Drive Overall Map

The Anthony Henday Drive Extension project was tendered by the City of Edmonton in July 2000, and would be the third road section built. The project involved the extension of the existing Anthony Henday Drive from Whitemud Drive to 45 Avenue; the finished road would be a 4-lane divided highway. The surface works portion of the project had the following tendered quantities:

Subgrade Preparation: 121,000 m^2

Aggregate Placement (20mm & 63mm Aggregate): 231,000 tonne

Superpave Asphalt: 33,000 tonne

Standard General Inc. was awarded the project as the prime contractor in July 2000. The job was completed in two parts; the first was completed during the summer and fall of 2000, while the remainder was completed the following year.

5.2 Construction Process – Anthony Henday Drive

During construction it was necessary to introduce buffers into the schedule. Due to a higher production rate, for example, the asphalt could be completed much more quickly than the aggregate. Therefore when the asphalt operation closed the gap between it and the aggregate operation, it was stopped until enough aggregate could be placed to begin the operation again. One of the contributing factors for not adjusting the schedule to allow for continuous asphalt placement was that there were other demands on the operation. With limited resources and different contractual requirements on several projects, it becomes very difficult to synchronize the operation perfectly. Therefore it

became more practical for Standard General Inc. to mobilize their paving crew several times in order to complete to the project. As mentioned in the previous chapter, the aggregate operation was closely linked to the subgrade operation. Poor weather can damage completed subgrade, so it was important for the subgrade operation not to get too far ahead of the aggregate operation.

5.3 Data Collection

The large quantities and relatively simple construction schedule made the Anthony Henday Drive Extension an excellent choice to simulate using a model created from the SPS Template. To validate a computer model, two types of data are required. First, input data for the model was required so that the same input parameters are used as the actual project. Second, validation data such as production rates, and resource utilization rates were required to compare with the model output. The output produced by a simulation model should yield relatively similar results as an actual project in order for the model to be validated. Both types of data came from a variety of sources; these included project time sheets, field quantity reports, trucking haul tickets, time studies and discussions with industry practitioners.

Field Quantity Reports & Time Sheets

After each day foremen of Standard General Inc., complete daily time sheets and material quantity reports. Material, labour and equipment used on a job are coded to specific processes and are entered into a computer database. This data was used to compile an as-built schedule, calculate production rates for each of the three operations (subgrade,

aggregate, asphalt), and to determine the operational buffers that where used for the project.

Trucking Haul Tickets

Trucking haul tickets were used to provide statistical data for the Trucks for the model. Each time a truck makes a delivery to the site, a haul ticket is collected and among other information the haul ticket includes the amount hauled by a particular tuck (tonne). Beta distributions were fitted to the haul ticket data for both aggregate and asphalt trucks.

Time studies

During the summer of 2000, the NSERC/Alberta Construction Industry Research Chair in Construction Engineering Management performed the “109th Street Rehabilitation & Underpass Demolition Productivity Study” in cooperation with Standard General Inc. One of the main focuses of the study was the asphalt paver; it was observed for specific periods of time, and during that time period several pieces of data was collected. Delays were categorized and timed, and production was measured. The results of the studies gave indications of paver utilization rates, ultimate paver production, truck positioning time, and delay time percentages. Beta distributions were fitted to both the ultimate paver production rate, and truck positioning time data.

Industry Practitioners

Discussions with several employees of Standard General Inc provided critical pieces of information, which was necessary for the SPS Template validation. Models created using

the SPS Template require several input parameters that are best determined with field experience. Triangular distributions were used for most of inputs obtained from industry practitioners, because they are easily understood; most experienced practitioners have a good feel for the minimum, average, and maximum production values of their specific industry.

5.3.1 Data for Model Input

Table 5-1 describes the model input data that was required to accurately model the Anthony Henday Drive Extension Project.

Several of the model inputs that were used in Table 5-1 are in the form of statistical distributions. Uniform (UNI), Triangular (TRI) and Beta (BETA) distributions were used. Distributions are used in simulation in an attempt to more closely model the actual process. Uniform and Triangular distributions are often used because for industry practioners (from which much of the data was collected) their meaning is easily understood. A Uniform distribution is simply a range of numbers evenly distributed. For example an input value with a UNI(1,10) distribution could be any number between 1 and 10. A Triangular distribution provides a low, high and mean of an input value. For example an input value with a TRI(1,3,10) distribution could be any number between 1 and 10 but the average of the values will be 3. A Beta distribution is more complicated. This type of distribution is good for representing data that has been previously collected because it is considered a flexible distribution. The input values that were determined through detailed analysis and data collection were fitted with Beta distributions.

Table 5-1: Anthony Henday Drive Validation Model Input Parameters

Element	Input Description	Value	Source
Construction Site	Total Road Area	123,000 m^2	Field Quantity Report
Subgrade Operation	Production Rate	UNI(550,700) m2/hr	Industry Practitioners
Aggregate Operation	Grader Production Rate Truck Dumping Time Aggregate Pull Subgrade Buffer	TRI(700,720,780) tonne /hr UNI(2,5) min. 1.74 tonne/m^2 12,500 m^2	Industry Practitioners Assumption Physical Property of Aggregate Field Quantity Report & Time Sheets
Asphalt Operation	Paver Placement Rate Truck Positioning Time Asphalt Pull Number of Pavers Aggregate Buffer	BETA (1.07,3.58,449.42,1804.80) tonne /hr TRI (0.50,0.90,2.00) min. 0.234 tonne/m^2 2 31,000 m^2	Paver Time Study Paver Time Study Physical Property of Asphalt Industry Practitioners Field Quantity Report & Time Sheets
Aggregate Pit	Truck Loading Rate Truck Prep. Time	UNI (500.00,600.00) tonne/hr UNI (2,3) min.	Industry Practitioners Industry Practitioners
Asphalt Plant	Production Rate Truck Load Time Storage Capacity Truck Prep. Time	TRI(300.00,325.00,400.00) tonne/hr UNI(2.00,3.00) min. 300 tonne UNI (2,3) min.	Industry Practitioners Industry Practitioners Physical Property of Asphalt Plant Industry Practitioners
Aggregate Haul Road	Length Ave. Speed Limit Expected Delay	70 km 90 km/hr UNI (5,10) min.	Industry Practitioners Assumption Assumption
Asphalt Haul Road	Length Ave. Speed Limit Expected Delay	24 km 90 km/hr UNI(5,10) min.	Industry Practitioners Assumption Assumption
Aggregate Trucks	Number Loaded Speed Empty Speed Capacity	23 90 km/hr 100 km/hr BETA (2.65,3.84,20.85,42.61) tonne	Industry Practitioners Assumption Assumption Truck Haul Tickets
Asphalt Trucks	Number Loaded Speed Empty Speed Capacity	18 90 km/hr 100 km/hr BETA (5.45,1.32,11.87,15.77) tonne	Industry Practitioners Assumption Assumption Truck Haul Tickets

Once the input data was collected, a model was created using the SWCR Template.

5.3.2 Anthony Henday Drive Extension Schedule Analysis

A detailed schedule analysis of the Anthony Henday Drive Extension project was preformed using both time sheets and field quantity reports. On each job that Standard General Inc. is awarded unique cost codes are assigned to every process associated with the project. Items such as labour hours, equipment hours, and field quantities are entered into a computer database on a daily basis. Data for the cost codes associated with subgrade preparation, aggregate placement, and asphalt paving was extracted from the database in order to perform the analysis. A daily record of time, and production quantity was assembled for each of the three operations, and with this information an as-built schedule was created. This information also provided the average production rates, and average operational buffers for the subgrade, aggregate, and asphalt operations. For purposes of comparison, only records that were associated with equipment production were used. The SWRC Template is not designed to include hand production, and therefore these data entries were omitted from the analysis. Table 5-2 outlines the as-built data collected for the Anthony Henday Drive Extension Project.

Table 5-2: Anthony Henday Drive Actual Project Data

Description	Subgrade Operation	Aggregate Operation	Asphalt Operation
Quantity	131,581.3 m^2	221,779.4 tonne	28,802.5 tonne
Duration	212.0 hrs	624.5 hrs	96.5 hrs
Production Rate	620.7 m2/hr	355.1 tonne/hr	298.5 tonne/hr
*Operational Buffer	n/a	12,500 m^2	31,000 m^2

* Used as input of the SPS Template model.

5.4 Simulation Model vs. Actual Project Comparison

Table 5-3 outlines the model outputs and actual project values that were used for comparison. Production rates were used for this comparison because they are often the most critical numbers for both estimating and job costing purposes.

Table 5-3: Anthony Henday Drive Simulation Model vs. Actual Project Output

Description	Model Output	Actual Output	Difference (%)
Overall Subgrade Production Rate (m^2/hr)	624.7	620.7	0.64
Overall Aggregate Production Rate (tonne/hr)	337.9	355.1	4.8
Overall Asphalt Production Rate (tonne/hr)	290.8	298.5	2.6
Paver Utilization Rate (%)	31.4	33.3	5.7
Paver Truck Change (%)	16.4	17.0	3.5
Project Duration (hrs)	677.7	733.5	7.6

5.4.1 Subgrade Operation

The overall production rate of the subgrade operation model output is extremely close to the actual project data. The reason for this is that this number was input based on industry practitioner experience, and is not affected by any of the model processes. In other words, the model output for this operation is expected to be very close to the model input.

5.4.2 Aggregate Operation

The overall production rate of the aggregate operation is affected mainly by the truck haul associated with this process. In other words the limiting factor with this operation is

the rate at which aggregate can be delivered to the site. A 4.8% difference between the actual project and the model output indicates that this process was modeled very effectively.

5.4.3 Asphalt Operation

As can be seen from the model output, the asphalt operations have been modeled very effectively using the SWRC Template. The difference between the model output and actual project data was a nearly perfect 2.6%. Because more data on the asphalt operation was collected, additional comparisons can be made. The paver utilization rate is the percentage of the time that the paver is actually placing asphalt compared to the total time of the operation. Time studies done during the 109th Street Rehabilitation and Underpass Demolition Productivity Study (109th Street Study) have indicated this number to be approximately 33.3%, which compares very closely to the model output of 31.4%. Additional comparisons can be made using truck change times and material delay statistics. The percentage of time that trucks are being changed in front of the paver has been documented by the 109th Street Study to be approximately 16.4%. This statistic indicates the percentage of time that trucks are repositioning and backing up to the paver. The model output suggests a truck change time of 17.0%, which again is extremely close to the data researched in the 109th Street Study.

5.4.4 Overall Project Duration

The final comparison between the model and the actual project data can be made using the project duration. Although a 7.6% difference between the actual project and the

model outputs is not very significant, an explanation for this could be because one of the key assumptions made by the model ensures that each of the three operations are completed using separate crews and equipment resources. Further investigation of the actual project reveals that this was not the case throughout the duration of the project. In certain instances crews used for the aggregate operation were used for subgrade operation and visa versa. This meant that during specific situations these operations were not completed separately, but rather in a cyclic manner, each sharing the same resources. In this case the production rates for each of the operations would not be affected by one another, however the overall duration of the project would likely be increased.

5.5 Conclusions

This chapter validates the SWRC Template, as a tool that is able to effectively model surface the surface works operations of road construction. A simulation model of the Anthony Henday Drive Extension Project was created using the SWRC Template developed in Chapter 4. A detailed analysis of the project was performed in order to compare the model outputs with actual data. The model was found to perform extremely well in that the key comparisons were extremely close to their actual project counterparts. The development and validation of a SPS tool for surface works operations is extremely useful. The template provides both researchers and industry practitioners with a tool that will enable them to perform various analytical functions including model sensitivity analysis, scenario analysis, and lean production theory analysis using a model that has been proven to closely resemble the actual construction process.

Chapter 6

Applying the Principles of Lean Construction to Simulation Models

6.1 Overview

The purpose of this Chapter is to develop guidelines for the incorporation of lean principles in simulation models. Once complete, these guidelines will be used to implement lean principles and measure their effects on road construction models created from the SWRC Template discussed in Chapter 5. Making use of the SWRC Template will not only help to better understand how these principles can be applied but also give significant insight into how they specifically affect road construction operations. There is an important difference between the experiments presented in this chapter and similar experiments performed by Al-Sudairi et al. (1999). In this work, lean principles are applied to a simulation model, built from a special purpose simulation template, and not to a stand-alone simulation model. This difference is very significant because, the lean principles that are implemented in this Chapter are done so using a generic set of guidelines that can be applied to any model created from the SWRC Template or otherwise.

The principles of lean production outlined by Koskela (1992) in Chapter 1 can be combined into three central themes:

1. Identify and deliver value to the customer: eliminate waste
2. Increase output value: pull inventory

3. Create reliable flow: reduce variability

6.1.1 Eliminating Waste

A construction process is comprised of those activities that add value to the finished project, and those that do not. A non-value adding activity is that which takes time, resources, or space but does not add value (Koskela, 1992). Koskela states that the three causes of non-value adding activities are design, ignorance, and the nature of production. Whatever the cause, according to lean principles, if these activities can be reduced or eliminated, waste in the process can be decreased. Eliminating waste is a fundamental concept of lean production theory.

6.1.2 Pulling Inventory

A central theme of lean production theory is to produce a product that meets customer requirements with zero waste. Koskela suggests that there are two types of customers for any given activity in a construction process, the next activity and the final customer. Howell defines waste as time, space, or material used in the performance of an activity that does not directly contribute value to the final customer. In other words time, space, or material spent by activities not accomplishing either the requirements of the next activity or the final customer can be considered waste. The term pulling inventory means that material is delivered to the process at the time it is needed. In most construction projects material is pushed through each process, that is, resources must wait for it to be delivered. As a result, it is the supply of material that pushes or drives the construction

process (Tommelein, 1998). Pulling material when resources require it is simply put, instant delivery.

6.1.3 Reducing Variability

Variability will exist in any process where operations are dependent on the delivery of material or products or where linked operations have different production rates. One solution that has been developed to respond to variation in construction projects is the use of buffers. According to Howel et al., buffers can serve at least three functions in relation to shielding work by providing a workable backlog;

1. To compensate for differing average rates of supply and use between the two activities.
2. To compensate for uncertainty in the actual rates of supply and use.
3. To allow differing work sequences by supplier and using activity.

Buffers are important tools because they allow two activities, whose productions are closely linked, to proceed independently of one another (Howell et al., 1994). The SWRC Template used to create the example model in this chapter has two buffers built into it. As described in Chapter 3, these buffers are used between the subgrade and aggregate operations, and between the aggregate and asphalt operations. They can be used to compensate between the varying production rates of these operations.

6.2 Guidelines for the Implementation of Lean Principles to Simulation Models

Lean production theory has been recently introduced to the construction industry. The construction industry, however, has rejected many ideas from manufacturing because of the belief that construction is different; construction has unique and complex projects in highly uncertain environments under great time and schedule pressure (Howell, 1999). This is true in many cases, however transferring the ideas from manufacturing to construction does not have to be a literal process. The core principals of lean production are concepts, not actions. Computer simulation provides an excellent tool that can be used to experiment with these concepts with no risk or cost. Implementing new methods on actual construction project could prove to be both time consuming and expensive (Sudairi et al., 1999). With a systematic approach, lean production principals can be applied and verified using computer simulation.

A number of experiments utilizing the developed SWRC Template were performed in the attempt to develop guidelines for the implementation of the lean principles described in the previous section into simulation models. Using the SWRC Template described in Chapter 4, various methods were used in an attempt to implement lean principles in a simulation model; these experiments led to the development of the following guidelines, which proved to be the most effective.

1. Select all non-value adding activities in the simulation model (candidates for improvement). Use the definition provided by Koskela in the previous section to focus on those activities that do not add value to the operation.
2. Set the task durations of the improvement candidates to zero (one at a time). Although in many cases eliminating these activities is not possible or practical, doing so will allow one to determine their significance on the model output.
3. Produce simulation results (run the simulation).
4. Sort the candidates in order of their significance to the simulation model. This will enable the improvement process to focus on those activities that have the greatest impact on model outputs.
5. Look for practical activity reduction solutions for the candidates starting with the activity that has the greatest potential for improvement.
6. Edit the simulation model to reflect zero time delivery of required materials. Although this may not be possible or practical, it will allow one to determine the effect that the material delivery process has on model outputs.
7. Produce simulation results (run the simulation).
8. Look for practical solutions to improve the material delivery processes (if required). If the material delivery process has a significant impact on model outputs, efforts should be made to make practical improvements.
9. Look for practical solutions to improve production activities. Only after the lean concepts (value adding activities, and pull driven flow) have been introduced to the model should the improvement be focused on production activities.

10. Introduce buffers to compensate for increased model variability, and differing production rates of linked operations. The lean production improvement process has generally been shown to introduce significant variability into processes. Buffers should be introduced as a final step to compensate for this effect.

6.3 Experimental Procedure – Implementing the "Lean" Guidelines

The proposed experimental procedure for testing the concepts of lean production is based on the guidelines presented in section 6.2. A base model is created using the SWRC Template that serves a benchmark for the experiment. To determine how a specific activity influences the outputs of the model, that activities duration is set to zero. The difference between the new model output and the base model output is the quantified impact that that activity has on the process. In other words, how sensitive the model (process) is to changes in that activity.

In order to implement the concepts of lean production using the proposed guidelines, a base model was created using the SWRC Template discussed in Chapters 4 and 5. The model used in this experiment is of a typical road section, 14m wide and 1.5 km long. The road structure is made up of 300mm of aggregate and 100mm of asphalt on prepared subgrade. For this experiment, three base models were used in order to determine how different haul distances effect model outputs when lean principles are introduced; those distances include 5 kms (short), 30 kms (medium), and 100 kms (long), and are used for both the aggregate and asphalt operations. Many of the same input parameters were used in the base model as for the validation model described in Chapter 5, however several

have been changed in order to more closely represent a typical road section; these inputs were obtained once again from industry practitioners. Figure 6-1 displays the layout of the simulation model and Table 6-1 displays the model input parameters used for the base model.

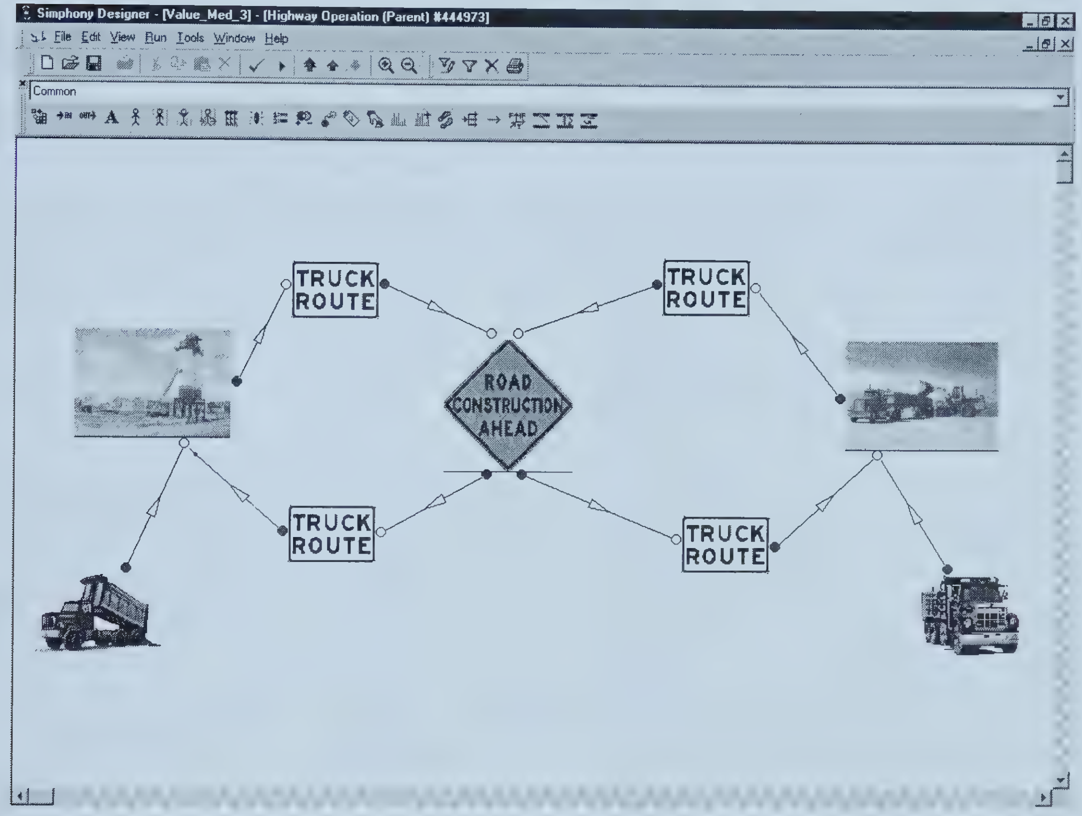

Figure 6-1: Experimental Model Setup

Table 6-1: Experiment Input Parameters

Element	Input Description	Value
Construction Site	Total Road Area	21,000 m2
Subgrade Operation	Production Rate	TRI(325,500,600) m2/hr
Aggregate Operation	Grader Production Rate Truck Dumping Time Aggregate Pull Subgrade Buffer	TRI(350,360,390) tonne /hr UNI(2,3) min. 0.71 tonne/m2 1,000 m2
Asphalt Operation	Paver Placement Rate Truck Positioning Time Asphalt Pull Number of Pavers Aggregate Buffer	BETA (1.07,3.58,449.42,1804.80) tonne /hr TRI (0.50,0.90,2.00) min. 0.234 tonne/m2 1 5,000 m2
Aggregate Pit	Truck Loading Rate Truck Prep. Time	TRI (200,325,550) tonne/hr UNI (2,3) min.
Asphalt Plant	Production Rate Truck Load Time Storage Capacity Truck Prep. Time	TRI(250,325,400) tonne/hr UNI(2,3) min. 300 tonne UNI (2,3) min.
Aggregate Haul Road (City)	Length Ave. Speed Limit Expected Delay	5, 30, 100 kms 85 km/hr UNI (5,10) min.
Asphalt Haul Road (City)	Length Ave. Speed Limit Expected Delay	5, 30, 100 kms 85 km/hr TRI (5,10) min.
Aggregate Trucks	Number Loaded Speed Empty Speed Capacity	12 90 km/hr 100 km/hr BETA (2.65,3.84,20.85,42.61) tonne
Asphalt Trucks	Number Loaded Speed Empty Speed Capacity	10 90 km/hr 100 km/hr BETA (5.45,1.32,11.87,15.77) tonne

In order to determine how the concepts of lean production effect the model, outputs must be chosen for comparison and must be measured the same for all sets of inputs. They must also represent quantifiable performance characteristics that the concepts of lean production aim to improve. The following list describes several important characteristics

that help to determine the performance of a construction process (adapted from Tommelein et al.).

- Resource Utilization: the percentage of time that a resource is working as compared to the total simulation time.
- Production Rate: the number of work units a resource actually completes in a given time period. A larger production rate may not always be desirable. As discussed in Chapter 3, linked activities with linear relationships can effect one another significantly when they have differing production rates.
- Project Duration: the time it takes to complete a project.
- Throughput: the number of work units complete divided by the project duration.

The above characteristics will serve as benchmarks for comparing the effect of lean construction principles on the computer model. The following section outlines the model outputs for the base case scenario for each of the operations.

6.3.1 Base Model Outputs

Table 6-2 outlines the general outputs for the base model, using the inputs described in Table 6-1.

Table 6-2: Overall Base Model Outputs

Description	Short Haul (5 kms)	Medium Haul (30 kms)	Long Haul (100 kms)
Highway Complete (m^2)	21,034.4	21,030.3	21,001.6
Project Duration (hrs)	57.8	77.8	188.7
Project Throughput (m^2/hr)	363.9	270.4	111.3

Subgrade Operations

The subgrade operation is not the focus of this analysis because its production rate is entirely dependent on the model input (a property of the SWRC Template discussed in Chapter 4). As a result the subgrade operation will not be discussed further.

Aggregate & Asphalt Operations

Table 6-3 outlines the outputs for the aggregate and asphalt operations, for each of the three haul distances.

Table 6-3: Base Model Outputs

Description	Short Haul (5 kms)	Medium Haul (30 kms)	Long Haul (100 kms)
Aggregate Operations			
Total Working Time (hrs)	44.6	55.6	148.5
Total Time (hrs)	44.6	55.6	148.5
Total Delayed Time (hrs)	0	0	0
Ave. Production Rate (tonne/hr)	337.8	268.4	100.6
Ave. Grader Utilization (% Working Time)	44.9	35.2	13.6
Number of Mobilizations	1	1	1
Asphalt Operations			
Total Working Time (hrs)	21.8	47.0	114.2
Total Time (hrs)	35.6	51.2	129.5
Total Delayed Time (hrs)	13.8	4.2	15.3
Ave. Production Rate (tonne/hr)	221.8	103.0	42.3
Ave. Paver Utilization (% Working Time)	35.6	16.7	7.4
Ave. Truck Change Time (% Working Time)	28.7	14.5	6.2
Number of Mobilizations	3	2	2

Figure 6-2, 6-3, and 6-3 display the velocity diagrams for each of the three haul distances.

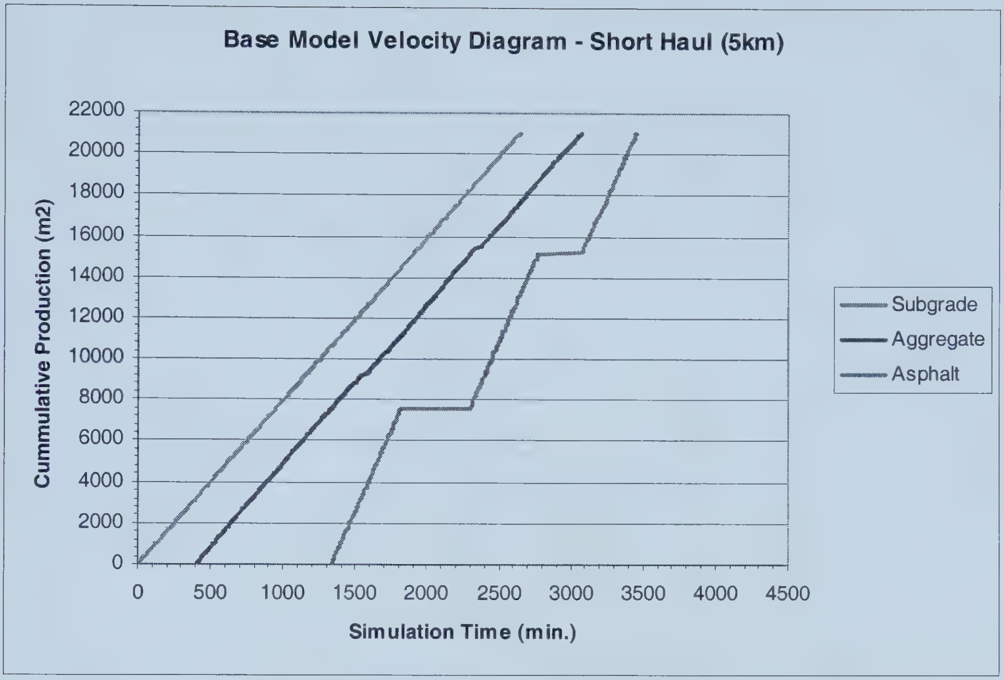

Figure 6-2: Base Model Velocity Diagram – Short Haul (5 kms)

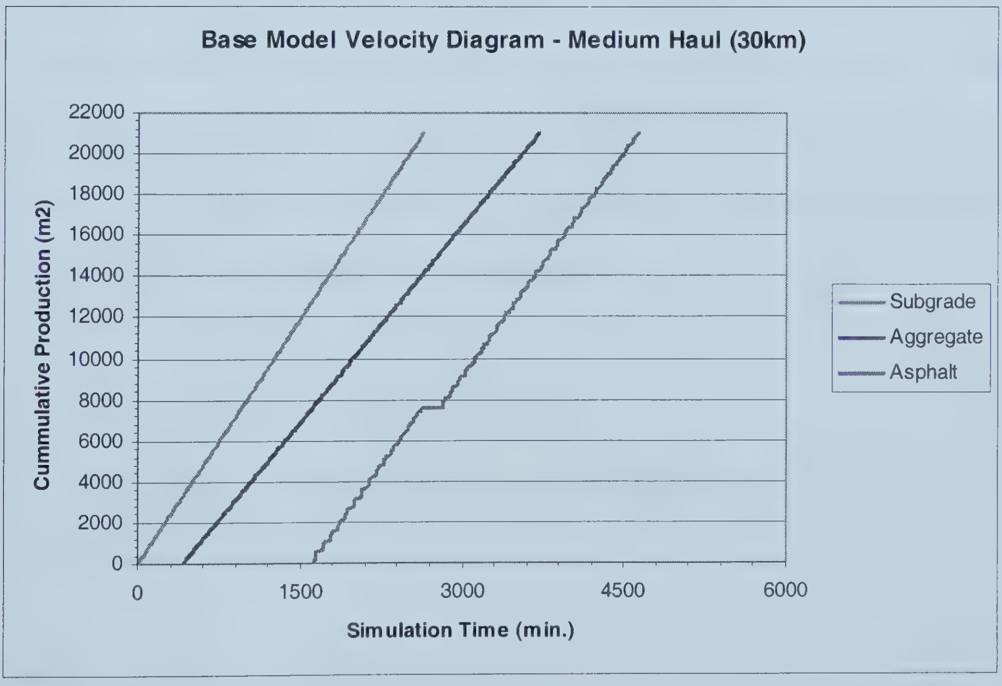

Figure 6-3: Base Model Velocity Diagram - Medium Haul (30 kms)

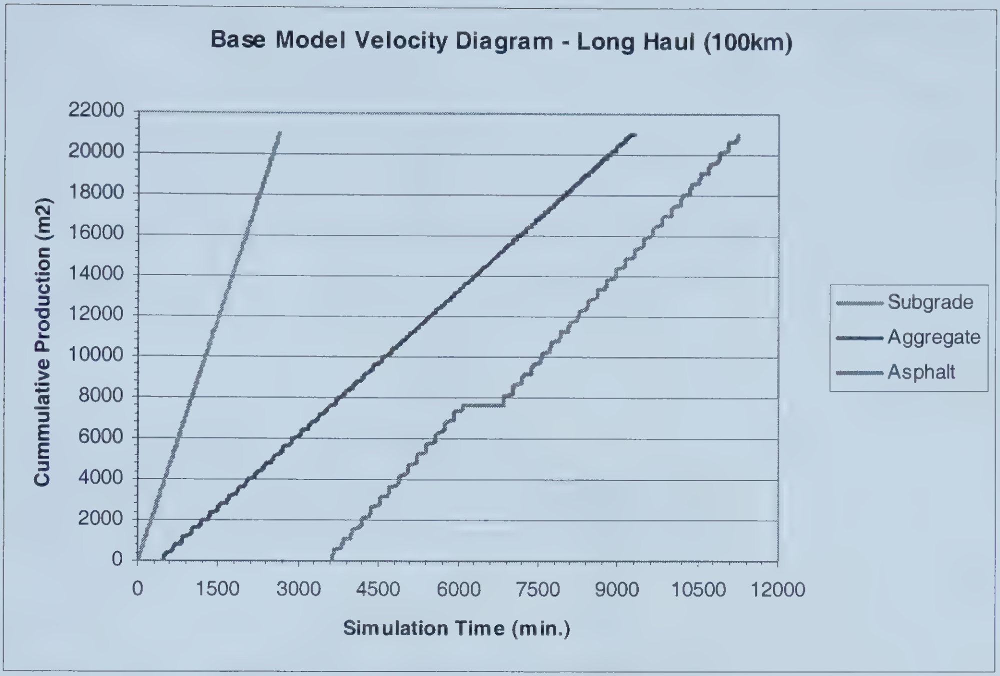

Figure 6-4: Base Model Velocity Diagram - Long Haul (100 kms)

As expected, when the haul distance for the aggregate and asphalt operations is increased, the overall project duration is increased, and the production rates for those processes decrease. With a base case established the computer model can now experimented with using the guidelines proposed in the previous section.

6.3.2 Implementing the "Lean Guidelines"

Each of the guidelines described earlier, will be implemented in this section, in order to quantify their impact on the base model.

Step One: Identify the candidates for improvement within the simulation model.

By examining the computer model, the first task is to determine which activities are value adding and which are non-value adding. A task can be considered value adding if it contributes value to either the final customer (product), or the next customer in the process. Table 6-4 distinguishes the activities in the model as either value adding or non-value adding.

Table 6-4: Value and Non-Value Adding Activities

Process	Activity	Value Adding?
Subgrade Operations	Subgrade Preparation	YES
Aggregate Pit	Truck Preparation Time	NO
	Loading of Trucks	NO
	Aggregate Transportation	YES
Aggregate Operations	Truck Dumping	NO
	Aggregate Placement	YES
Asphalt Plant	Truck Preparation	NO
	Asphalt Production	YES
	Loading of Trucks	NO
	Asphalt Transportation	YES
Asphalt Operations	Position Truck	NO
	Asphalt Placement	YES

Material transportation is an activity that is difficult to determine. Although it does not add value to the finished product, it is a valuable task with respect to the aggregate or asphalt production activities. Without the material, these value-adding activities could not take place. For this reason material transport is considered to be a value adding activity.

Step Two: Set the activity durations of the improvement candidates to zero.

In order determine the impact that non-value adding activities (improvement candidates) have on the simulation model they were removed and the simulation was run. For the purpose of this experiment all of the improvement candidates durations were set to zero at the same time in order to determine the models "potential for improvement" in this area. The model outputs from this procedure are compared to the base model in Table 6-5.

Step Three: Produce simulation results.

Table 6-5: Value Adding Activities Model Output vs. Base Model Output

Description	% Change from Base Model		
	Short Haul	**Med. Haul**	**Long Haul**
Project Duration	-18.7%	-23.5%	-7.9%
Project Throughput	17.3%	24.5%	1.7%
Aggregate Operations			
Total Working Time	-56.5%	-34.2%	-16.6%
Total Time	-16.6%	-26.6%	-16.6%
Ave. Production Rate	117.1%	44.8%	14.1%
Ave. Grader Utilization	118.0%	44.9%	15.4%
Number of Mobilizations	500.0%	500.0%	0.0%
Asphalt Operations			
Total Working Time	-41.3%	-27.0%	-2.0%
Total Time	-26.7%	-26.0%	-6.7%
Ave. Production Rate	62.8%	30.6%	-2.6%
Ave. Paver Utilization	47.8%	34.7%	16.2%
Number of Mobilizations	0.0%	0.0%	0.0$

Table 6-5 shows an overall improvement of the models performance when the non-value adding activities are removed from the process, however the improvements change as the

haul distances vary. Generally speaking, the percent improvement, as compared to the base model, decreased as the haul distances increased. The reason for this is that as the haul distances increase the material delivery delay time increases; in other words, as the share of non-value adding activities goes down, their impact becomes relatively small. Although the statistics collected show a great improvement, velocity diagrams of each haul distance case yield interesting results. Figures 6-5, 6-6 and 6-7 display the velocity diagrams for each of the haul distances.

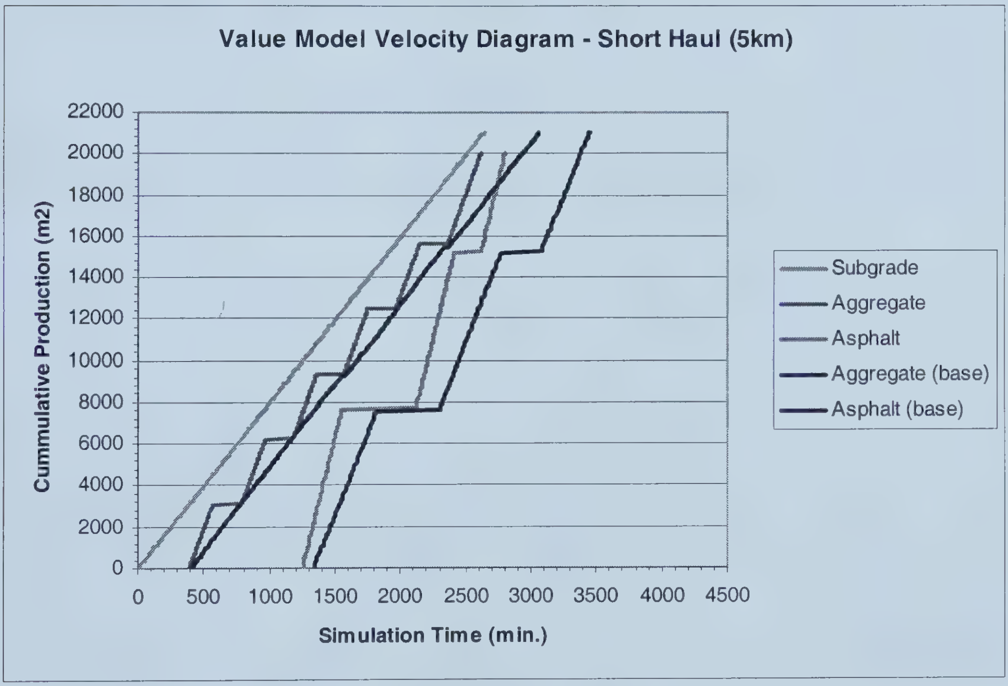

Figure 6-5: Value Adding Model vs. Base Model – Velocity Diagram (Short Haul, 5 kms)

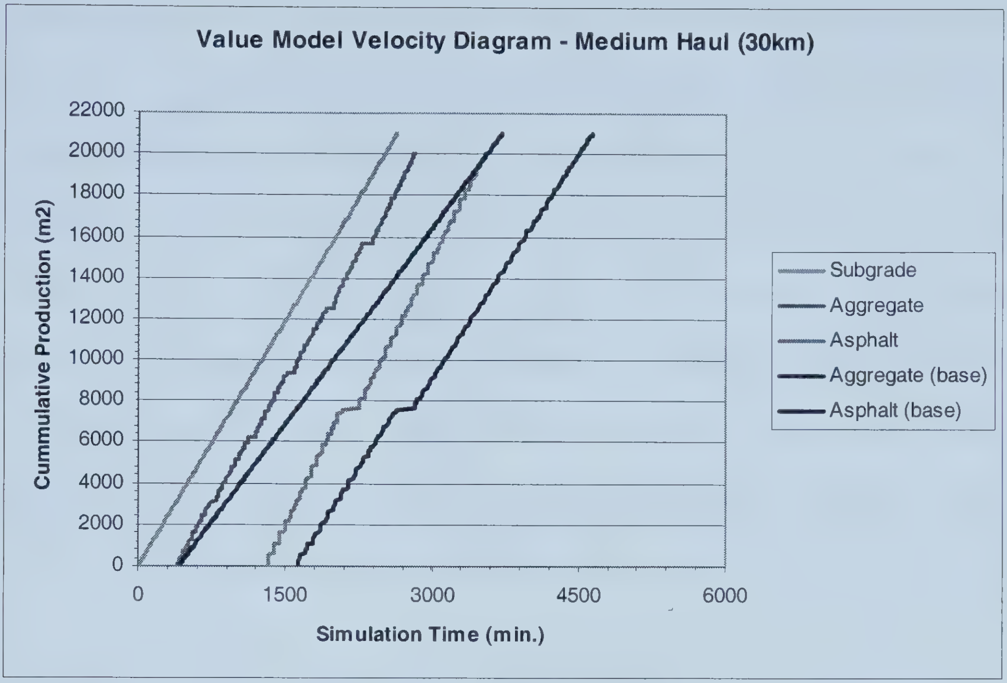

Figure 6-6: Value Adding Model vs. Base Model - Velocity Diagram (Med. Haul, 30 kms)

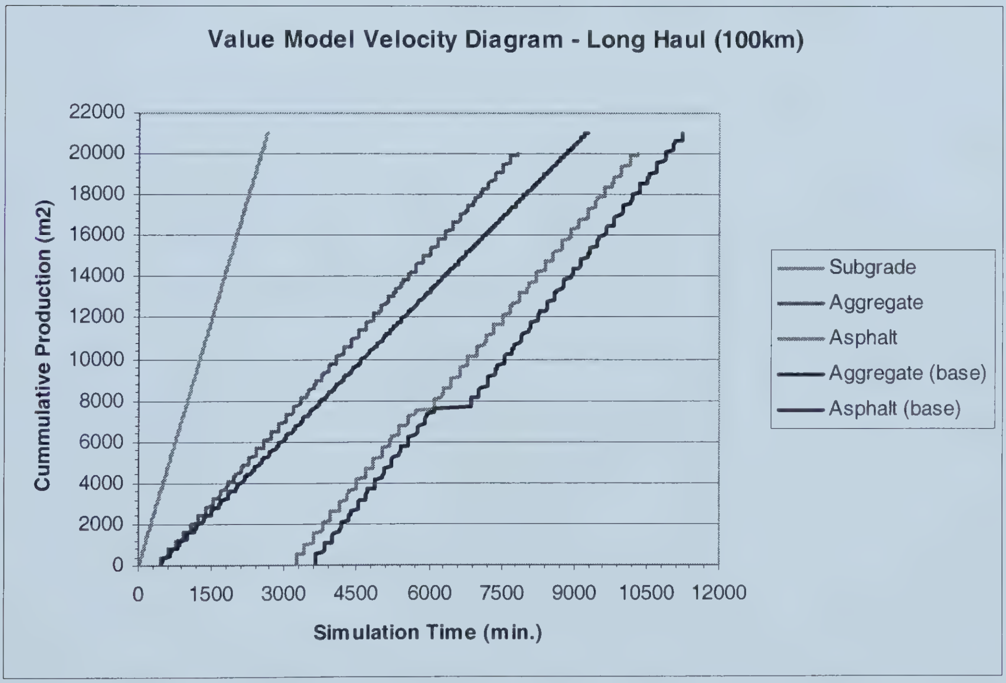

Figure 6-7: Value Adding Model vs. Base Model - Velocity Diagram (Long Haul, 100 kms)

As mentioned, the long haul case did not change as significantly as the medium and short haul cases. In those cases (more so in the short case) significant variability was introduced as non-value adding activities were eliminated. The term variability in this respect is meant to indicate non-continuous production, and not necessarily erratic production values. The aggregate operation, for example, was stopped due to operational interference with the subgrade process a total of 5 times (in both cases) compared with zero times in the base model (this will be discussed further in Step 10.). The data collected from this experiment indicate that in surface works operations, non-value adding activities have the greatest effect on the process when the haul distances are short.

Step Four: Sort the candidates in order of their significance to the simulation model.

It is clear that non-value adding activities combine to have a significant effect on model outputs, however it is also desirable to know which non-value adding activities have the most significant effect, because it enables industry practitioners to have a starting point when deciding which activities they should look more closely at when attempting to improve the system. Using the same experimental procedure as in Step Three, each non-value adding activity was eliminated, one at a time, so that their significance could be ranked. The results of this process are summarized in Table 6-6.

Table 6-6: Ranked Non-Value Adding Activities

Non-Value Adding Activity Eliminated	Production Rate (tonne/hr)	% Change	Rank
Short Haul (5 kms)			
Aggregate Operations			
Truck Dumping at Site	340.0	0.65%	2
Truck Prep. Time at Pit	338.6	0.24%	3
Truck Loading at Pit	700.7	107.4%	1
Asphalt Operations			
Truck Prep. at Plant	321.0	45.2%	2
Truck Loading at Plant	325.6	46.8%	1
Truck Position at Site	314.4	41.7%	3
Medium Haul (30 kms)			
Aggregate Operations			
Truck Dumping at Site	282.8	5.4%	2
Truck Prep. Time at Pit	279.0	3.9%	3
Truck Loading at Pit	294.1	9.6%	1
Asphalt Operations			
Truck Prep. at Plant	112.6	9.3%	2
Truck Loading at Plant	113.5	10.2%	1
Truck Position at Site	109.8	6.6%	3
Long Haul (100 kms)			
Aggregate Operations			
Truck Dumping at Site	107.4	6.8%	2
Truck Prep. Time at Pit	105.2	4.6%	3
Truck Loading at Pit	108.5	7.9%	1
Asphalt Operations			
Truck Prep. at Plant	49.9	18.0%	2
Truck Loading at Plant	50.6	19.6%	1
Truck Position at Site	49.8	17.7%	3

The data presented in Table 6-6, suggests several interesting results. For the aggregate operation, the number 1 ranked was Truck Loading at the Pit for each of the three haul distances. For the short haul distance, however, the improvement was much more significant than for the other hauls. This is because when the loading activity was eliminated, the short haul resulted in an excess of trucks (enough trucks were hauling to ensure that the Grader was utilized close to 100% of the time. Truck dumping at the site,

and truck preparation at the pit were shown have a greater effect on production than loading of aggregate at the pit. For the asphalt operation, the improvements seen were much more equally shared the candidates, however eliminating truck loading at the plant consistently improved the production rate for all of the haul distances.

It should be noted that the impact of reducing non-value adding activities on a simulation model greatly depends on the complexity of that model. Lee et al. point out that when activities are simplified for analytical purposes waste in those activities may go unnoticed. The relative simplicity of a computer simulation model compared to actual construction processes result in certain activities being considered value adding that may have non-value adding tasks embedded within them. For example, in an actual construction process the asphalt placement activity might involve, inspection, materials testing, survey checks and/or equipment maintenance, all of which are considered non-value adding. Analyzing activities to this degree becomes impractical using computer simulation because of the highly complex and detailed simulation models that would be required. Such complex models would be less flexible in terms of their applications, and difficult to use.

Step Five: Look for practical activity reduction solutions for improvement candidates.

For this step modelers and industry practitioners should attempt to reduce the share of the improvement candidates identified in Step 1. In many cases it will be impractical to eliminate these activities from the process, however if one starts with the activity that has the greatest impact on the model performance (form Step 4), it may be possible to reduce

its share. This can be done by analyzing the activity at a more detailed level than the model does. In doing so, an activity's sub-processes can be broken down, and room for improvement may be found.

Step Six: Edit the simulation model to reflect zero time delivery of materials.

To determine the impact that the material delivery process has on the model outputs the model is changed to reflect zero time delivery for both aggregate and asphalt. Accomplishing this can be done by increasing the number of resources transporting the material to the point where the resources that require them are utilized 100% of the time. In the example model this translates into the haul trucks waiting for the aggregate and asphalt operations rather than the other way around. Table 6-7 illustrates the model output that results from making this change.

Step Seven: Produce simulation results

Table 6-7: Pulling Material Model Output vs. Base Model

Description	% Change from Base Model		
	Short Haul	**Med. Haul**	**Long Haul**
Highway Complete	-	-	-
Project Duration	-20.2%	-40.7%	-75.6%
Project Throughput	16.6%	60.9%	284.0%
Aggregate Operations			
Total Working Time	-66.4%	-73.0%	-89.9%
Total Time	-17.7%	-34.0%	-75.3%
Ave. Production Rate	180.3%	252.7%	841.1%
Ave. Grader Utilization	127.7%	184.1%	635.3%
Number of Mobilizations	500.0%	500.0%	500.0%
Asphalt Operations			
Total Working Time	-42.7%	-73.4%	-89.1%
Total Time	-28.1%	-50.0%	-80.2%
Ave. Production Rate	66.7%	258.9%	774.0%
Ave. Paver Utilization	45.8%	210.8%	601.4%
Ave. Truck Change Time	67.9%	232.4%	677.4%
Number of Mobilizations	0.0%	50.0%	50.0%

Table 6-7 shows an overall improvement of the models performance when the model is changed to reflect zero time delivery, however the improvements affect the model in the opposite way that the non-value adding activities did. Generally speaking, the percent improvement, as compared to the base model, increased as the haul distances increased. The reason for this is that as the haul distances increase so does the amount of time associated with material delivery. For large haul distances (if the number of haul trucks is kept the same), the room for improvement is also large. Figures 6-8, 6-9, and 6-10 display the velocity diagrams for each of the three haul distances.

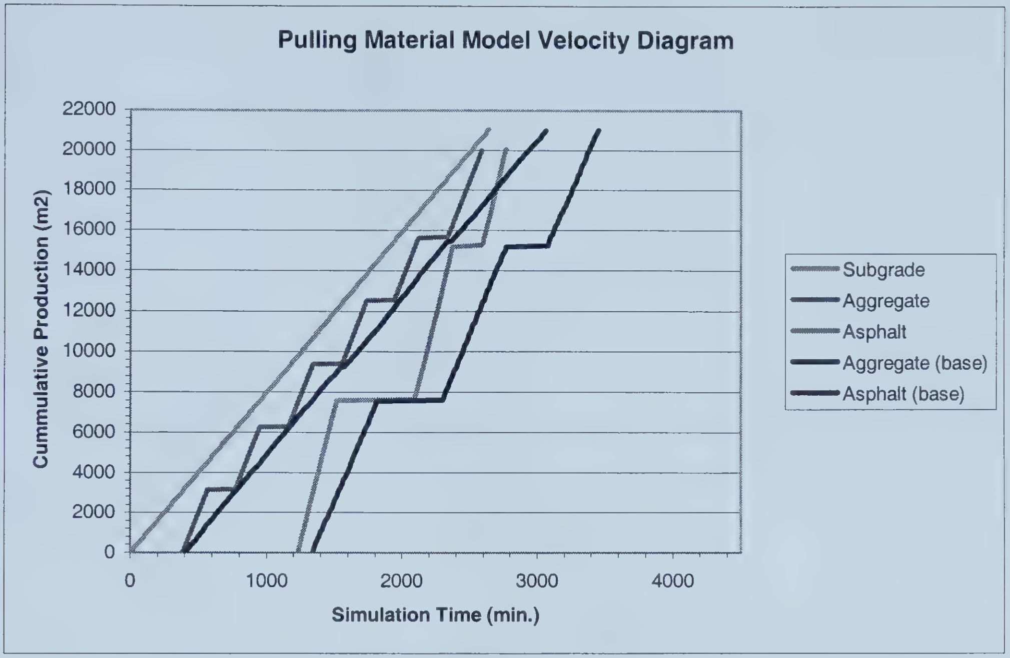

Figure 6-8: Pulling Material Model vs. Base Model – Velocity Diagram (Short Haul, 5 kms)

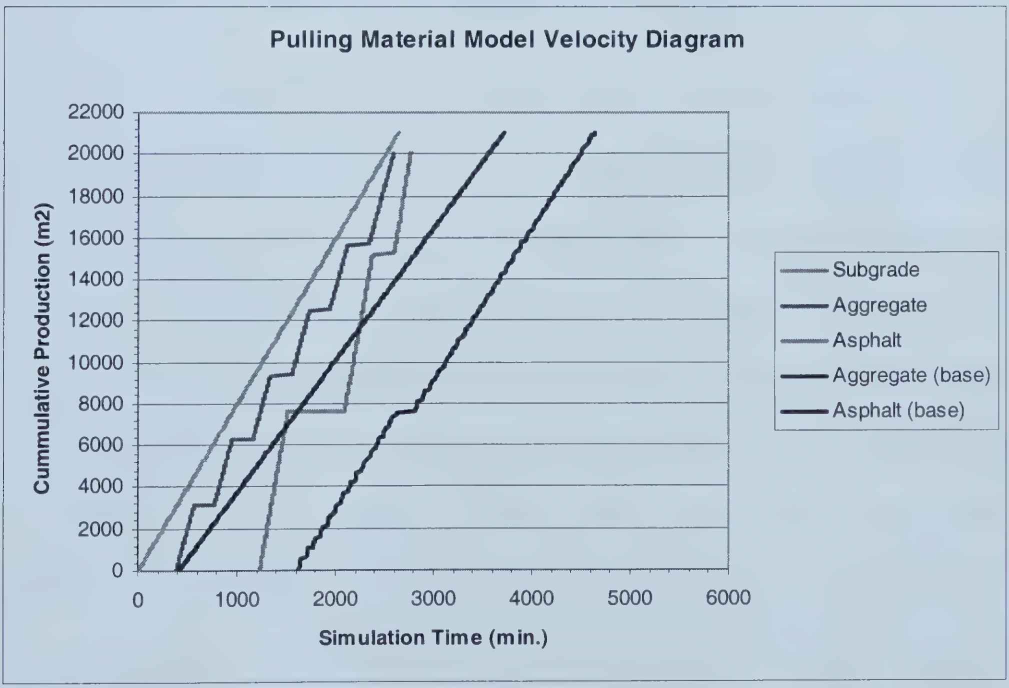

Figure 6-9: Pulling Material Base Model - Velocity Diagram (Med. Haul, 30 kms)

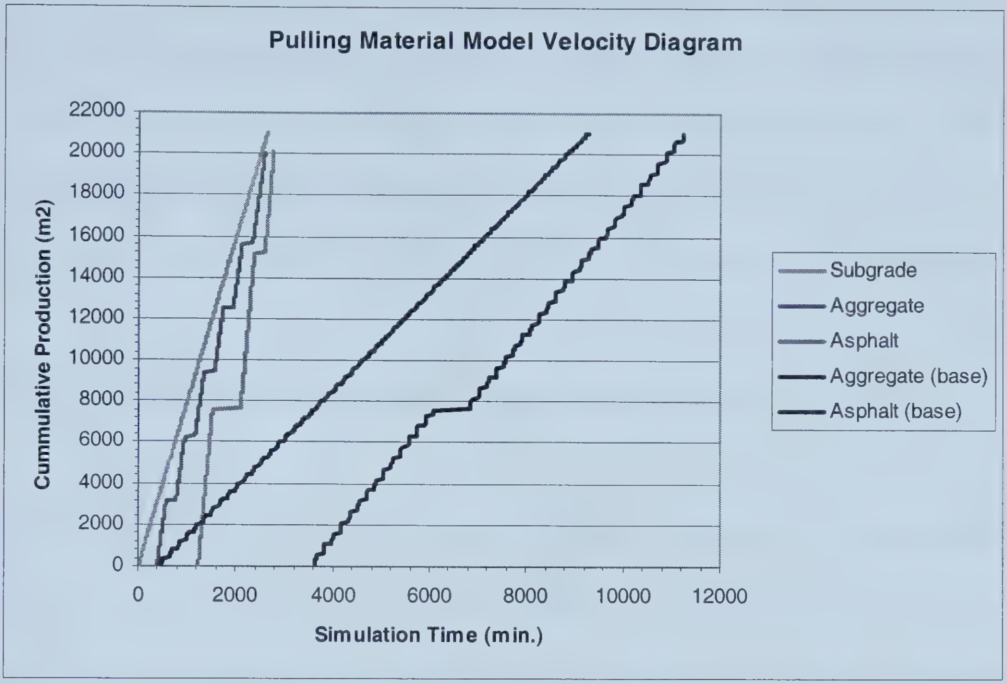

Figure 6-10: Pulling Material Model vs. Base Model - Velocity Diagram (Long Haul, 100 kms)

Although an opposite effect was had by the "pulling material" model in terms of the reaction to haul distances, a similar effect was observed in terms of process variability. The aggregate operation, for example, was stopped due to operational interference with the subgrade process a total of 5 times (in both cases) compared with zero times in the base model (just as in the non-value adding experiment). This will be discussed in the next section, however it is clear that introducing the concepts of lean production increase the differences in the operational production rates. The data collected from this experiment indicate that in surface works operations, "pulling" material rather than "pushing" it has the greatest effect on the process when the haul distances are long.

Step Eight: Look for practical solutions to improve the material delivery process.

This step is the same Step 5, except it applies to material delivery activities. In many cases it will be impractical to eliminate these activities from the process, however it may be possible to improve them by analyzing the process at a more detailed level. This exercise may include choosing better haul routs, selecting haul trucks with larger capacities, or brainstorming with suppliers to develop a new material delivery plan.

Step Nine: Look for practical solutions to improve production activities.

Once waste within the process has been thoroughly addressed by implementing lean production concepts, a closer look can be made at the activities directly associated with production (those activities that were considered value-adding in Step 1). Improvement of these activities may include the need to upgrade machinery, technology or construction practices.

Step Ten: Introduce buffers to compensate for increased model variability.

The results of changing the base model to reflect value-adding activities and zero time delivery showed significant improvements with regard to production rates, however the velocity diagrams shown in this section, demonstrate that operational buffers are required to control the impact that linked unbalanced operations have on one another. Howell et al. (1993) recommend that "Once an operation is underway, isolating sub-cycles by establishing buffers and eliminating shared resources is the first step to performance improvement in uncertain and/or unbalanced situations". While buffers are certainly

necessary in order to achieve a balanced system, they should not be the first step towards process improvement. The base model velocity diagram for the medium haul distance (Figure 6-3) depicts a fairly balanced system. The production lines of each operation are nearly parallel. As lean concepts were introduced, the processes within the model became unbalanced which resulted in operational interference. Therefore, it only makes sense to adjust the operational buffers only after the other lean concepts are introduced into the model; doing otherwise would be counter-productive. Buffer optimization can be done to reduce model variability by running the model several times and experimenting with different buffer sizes.

6.4 Experimental Findings and Conclusions

The improvements seen by the implementation of the elimination of non-value adding activities and from pulling material through the process were significant. By doing so the hourly production rate, resources utilizations, and project duration improved dramatically.

In terms of experimental findings, more important than which lean principle had the greatest effect is the effect itself. Sensitivity analysis using lean principles has shown that the potential for improvement by focusing on non-value adding and material delivery activities and then optimizing using buffers can improve a process significantly. Current thinking in the construction industry focuses improvement on activities that are directly linked with production; this experiment has shown that there is great improvement

potential to be had by focusing on other aspects of the operation as well. This is likely the case for processes other than road works.

An important feature of this work that distinguishes it from other lean production / simulation experiments, is that it was done using a SPS template. Other such experiments use stand-alone models to demonstrate lean principles. These models require both knowledge of computer programming, and of computer simulation techniques. The SWRC Template is flexible enough to model many road construction projects, without the need for such specialized knowledge

Although the results of this experiment are specific to surface works operations, the generic approach that was used to implement lean production principles are general enough that they could be used on any simulation model, regardless of the domain.

Chapter 7

Conclusions and Recommendations

7.1 Research Summary

The research contained in this thesis ultimately presents a systematic approach for the application of lean production theory in computer simulation models. This is accomplished through the development and experimentation with a special purpose simulation template designed for use in surface works operations of road construction. This research was conducted in collaboration with Standard General Inc., and the NSERC/Alberta Construction Industry Research Chair in Construction Engineering Management. The research was conducted in six major steps.

The first step of the research was the detailed understanding of the processes involved with surface works operations of road construction. This was accomplished in three ways. Detailed activity analysis of the key processes in road construction was performed during the summer of 2001, which provided statistical data on operational production rates and productivities. Discussions with industry practitioners (employees of Standard General Inc.) provided key information and insight, and personnel experience supplemented any additional information.

The second step of the research was the extraction of the actual construction processes of surface works operations for the purposes of simulation. Simplification of the actual

construction processes, and logical/mathematical relationships are required in order to create a computer simulation tool that is able to effectively model an operation.

The third step of the research was the development of a special purpose simulation template that can be used to create computer models of surface works operations in road construction. The was accomplished using Simphony (Hajjar and AbouRizk), which is a simulation platform that can be used to build both general and special purpose simulation tools (Appleton , 2002). Validation of the SPS Template was accomplished in step four by using it to create a model of the Anthony Henday Extension Project, which was completed in 2001 by Standard General Inc.

The fifth step in the research was the development of a generic approach for the implementation of lean production principles for use on all computer models and actual construction projects.

The final step involved the experimentation with the models created with the validated SWRC Template, using the guidelines developed in step five. These experiments produced results on the effects of the concepts of lean construction. Specific findings were made with regard to surface works operations.

7.2 Research Contributions

This research has led the following contributions:

1. The development of a systematic approach for the application of lean production theory in computer simulation models.

2. The development of a special purpose simulation template that can be used to create flexible computer simulation models of surface works operations in road construction.
3. Significant insight was gained as to how the key concepts of lean production theory can improve the surface works operations of road construction.

Lean production can be summarized into three main points; 1) eliminate or reduce all activities that do not add value to the final product, 2) pull material through the process (instant delivery of required materials), and 3) reduce variability by controlling uncertainties within the process. Recently the concepts of lean production have been introduced to the construction industry, however little work has been done to integrate them with the concepts of computer simulation.

This thesis presents a framework for implementing the concepts of lean production into computer simulation models. By creating a generic approach that practitioners can use to apply lean principles to any computer model regardless of the domain. This is important because it enables users to apply lean principles to simulation models and helps to bring them closer to applying them to actual construction projects.

In addition, this thesis describes the development of a special purpose simulation template for surface works operations of road construction (SWRC Template). This SPS tool allows practitioners to create flexible models of surface works operations in road construction. Model outputs can be used perform various analytical functions including

model sensitivity analysis, scenario analysis, and lean construction theory analysis. Using the SWRC Template it has also been established how lean production theory can be used to improve road construction operations significantly.

7.3 Recommendations

During the course of this research, the following recommendations have been noted for further research in this field.

1. This research describes a method for the application of lean principles in computer simulation models. Additional work should be done to incorporate these principles into a simulation tool. The SWRC Template, for example, could be modified to assist the user in applying lean concepts, by imbedding them within the simulation elements.
2. Further refinement of the SWRC Template could be done in an attempt to account for future developments discussed in Chapter 4. Doing so would result in a simulation tool with greater flexibility that more closely describes the actual construction process.
3. Additional SPS tools can be used to further describe the application of lean principles in computer simulation. The methods descried in this research should be tested and refined by applying them to a variety of simulation models.
4. Expanding the SWRC Template to include a variety of equipment choices, and crew configurations would greatly enhance the flexibility of models created with

it. Additional research would be required to gather the appropriate data, and integrate it into the SWRC Template.

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APPENDIX A

SWRC Template User Manual

SWRC Template

USER Manual

Jack Farrar

May 21, 2002

Table of Contents

Table of Figures

1.0 Introduction

This purpose of this user manual is to provide step by step instructions for the creation of a simulation model using the Surface Works in Road Construction (SWRC) Template. The template allows one to create simulation models that closely represent actual conditions for the purposes of scenario analysis, sensitivity analysis, and lean construction theory analysis.

2.0 Element Descriptions

2.1 Surface Works Road Construction Parent Element

The Surface Works Road Construction Parent element, shown in Figure 1, acts as a container for the model. It serves only this purpose, however a model cannot be created unless it is within this element. All elements of the model are child elements of the SWRC Parent Element.

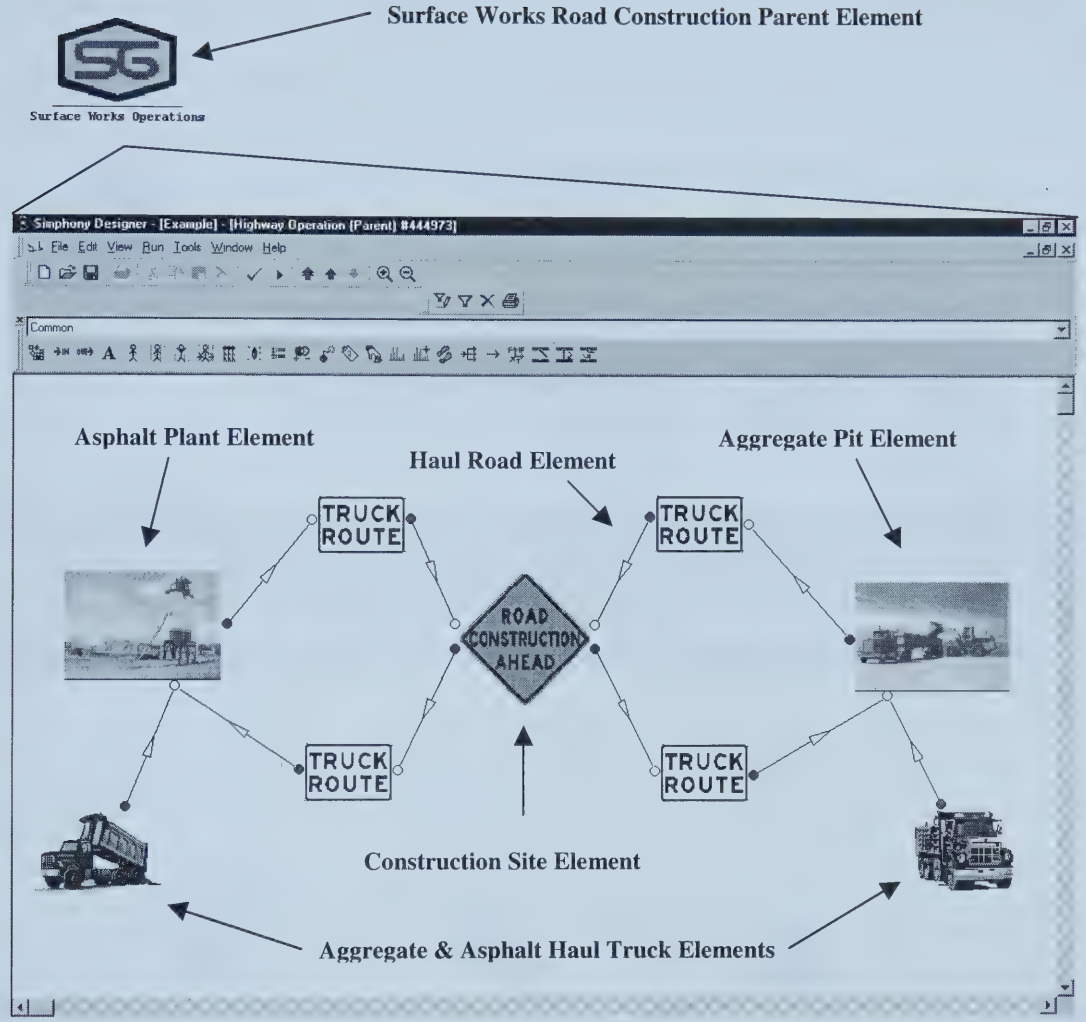


Figure 1: Surface Works Road Construction Parent Element and Example Model

2.2 Construction Site Element

The Construction Site Element, shown in Figures 1 and 2, is the heart of the SWRC Template. The Construction Site's child elements (Figure 2) are the three operations of surface works road construction (Subgrade, Aggregate, and Asphalt). The total area of

the constructed road is entered as an attribute for the Construction Site element, and the outputs include the areas completed for the three operations, the total project duration, and the project throughput.

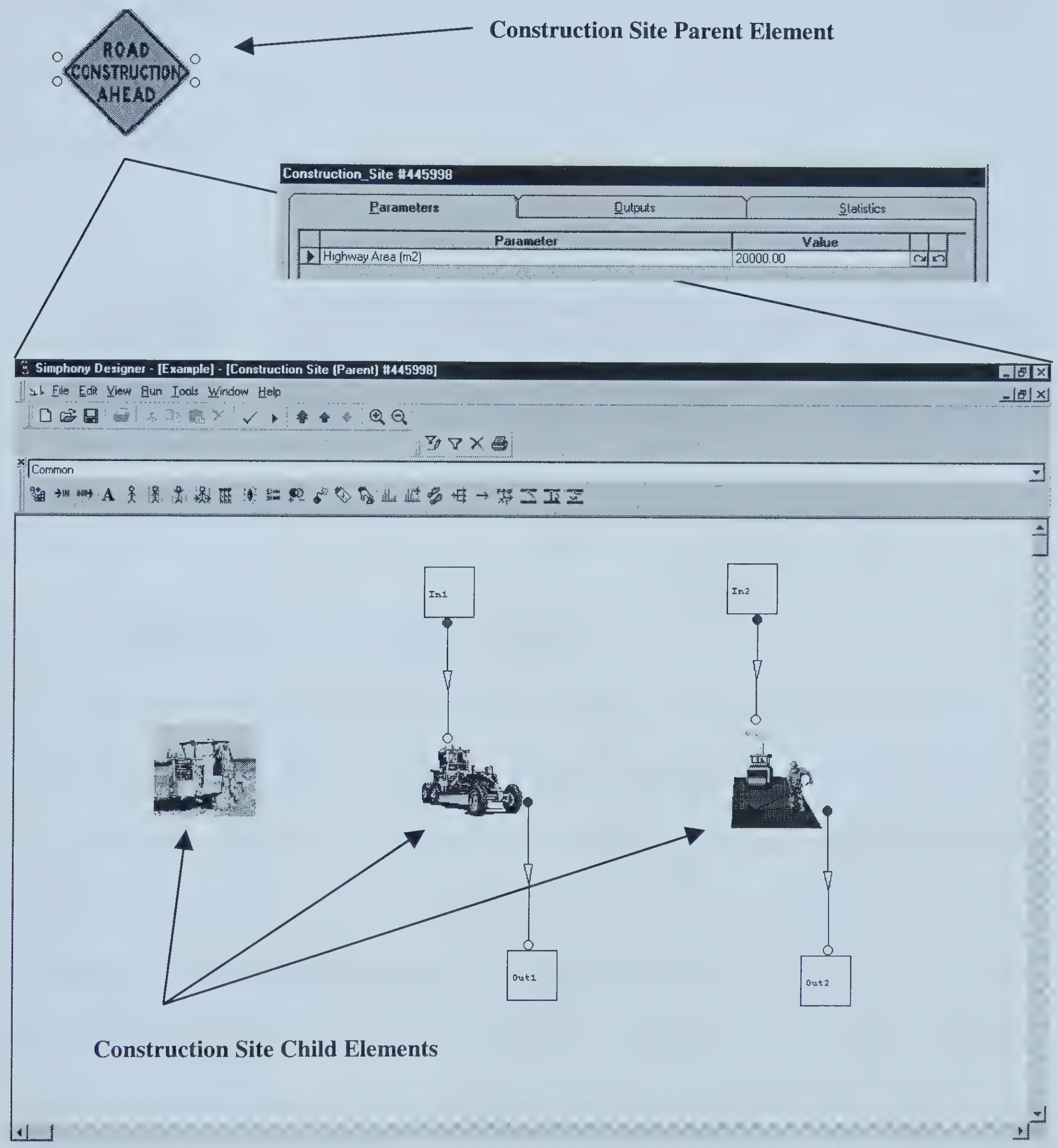


Figure 2: Construction Site Child Elements

2.3 Subgrade Operation Child Element

The Subgrade Operation Element, in Figures 2 and 2, represents the Subgrade operation. Its only attribute is the Subgrade Production Rate (m^2/hr) and its outputs include Subgrade Completed (m^2), Subgrade Operation Duration (hrs), and Average Subgrade Production Rate (m^2/hr). Common elements are used here to model the subgrade operation processes.

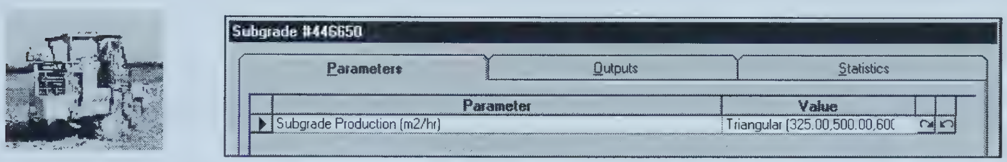


Figure 3: Subgrade Operations Modeling Element

2.4 Aggregate Placement Child Element

The Aggregate Placement Element, shown in Figures 2 and 4, represents the aggregate site placement process and its attributes include Aggregate Placement Rate (tonne/hr), Truck Dumping Time (min.), Aggregate Pull (tonne/m^2), and Subgrade Operation Buffer (m^2). The production rate and dumping time can both be entered as statistical distributions, while the aggregate pull and subgrade buffer must be entered as constant numbers. The outputs for this element include Aggregate Placed (tonnes), Aggregate Operation Overall Duration (hrs), Aggregate Placement Duration (hrs), and Average Aggregate Production Rate (tonne/hr). Statistics generated include Grader Utilization (%), Labour Utilization (%), Truck Cycle Time (min.), Hourly Production (tonne/hr),

Truck Waiting Time (min.), and Aggregate Running Total (tonne). Common elements are used to model the aggregate operation processes.

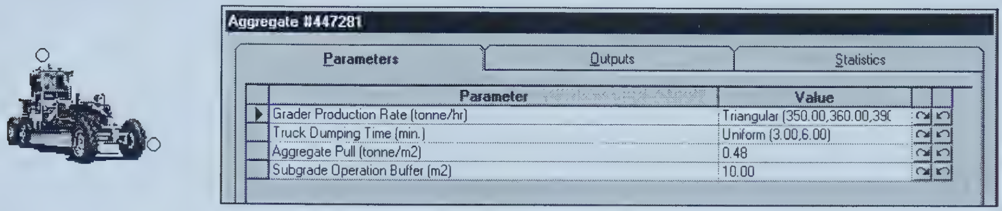


Figure 4: Aggregate Placement Element

2.5 Asphalt Placement Child Element

The Asphalt Placement Element, shown in Figures 2 and 5, represents the Asphalt operation and its attributes include Number of Pavers, Asphalt Placement Rate (tonne/hr), Truck Positioning Time (min.), Asphalt Pull (tonne/m^2), and Aggregate Operation Buffer (m^2). The outputs for this element include Asphalt Placed (tonne), Asphalt Operation Overall Duration (hrs), Asphalt Placement Duration (hrs), and Average Asphalt Placement Rate (tonne/hr). The Asphalt Operation element contains several statistics similar to the Aggregate Operation; they include Paver Utilization (%), Truck Cycle Time (min.), Hourly Placement Rate (tonne/hr), Truck Waiting Time (min.), Asphalt Running Total (tonne), and Truck Change Time (%). Common elements are used here to model the asphalt operation processes.

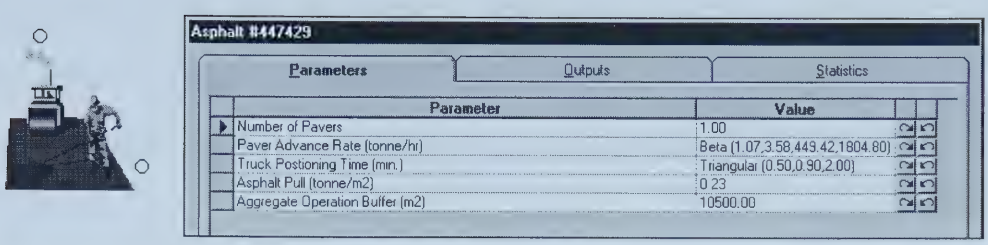


Figure 5: Asphalt Placement Element

2.6 Asphalt Plant Element

The Asphalt Plant Element, shown in Figures 1 and 6, represents the Asphalt Plant where asphalt is produced for the Construction Site. The attributes associated with it are Rate of Production (tonne/hr), Load Time per Truck (min.), Storage Capacity (tonne), and Truck Preparation Time (min.). The statistics produced by this element include Plant Utilization (%), Hourly Production (tonne/hr), Truck Waiting Time (min.), and Running Total (tonne). Common elements are used here to model the asphalt plant processes.

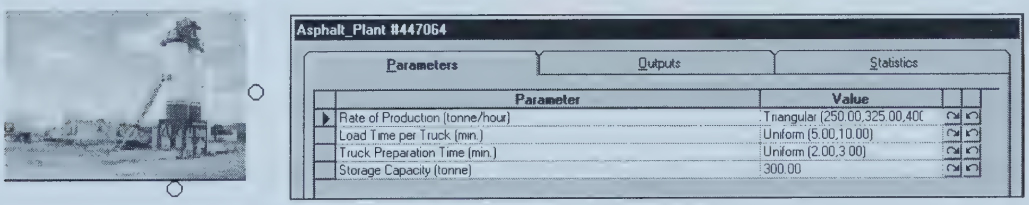


Figure 6: Asphalt Plant Element

2.7 Aggregate Pit Element

The Aggregate Pit Element, shown in Figures 1 and 7, represents the Aggregate Pit where aggregate is loaded for the haul to the Construction Site. Its attributes include the Aggregate Loading Rate (tonne/hr), and Truck Preparation Time (min.). Its only output

is Total Aggregate Loaded (tonne). The statistics produced include Pit Utilization (%), Hourly Production (tonne/hr), Truck Wait Time (min.), and Running Total (tonne). Common elements are used here to model the aggregate pit processes.

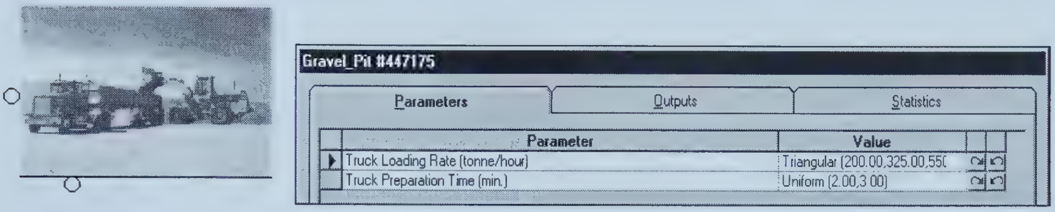
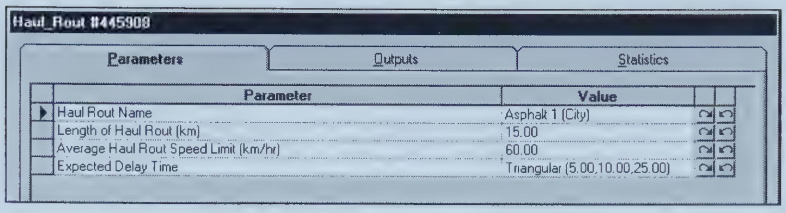


Figure 7: Aggregate Pit Element

2.8 Haul Road Element

The Haul Road Element, shown in Figures 1 and 8, represents a Haul Road to be used by either Aggregate Trucks or Asphalt Trucks. The Haul Road element can be used multiple times, and joined together with other Haul Roads. For example if the aggregate haul route was partially on the highway and partially through a city, two haul roads could be joined to represent each section (each with their own characteristics). The attributes for this element include Haul Road Name, Length of Haul Road (km), Average Haul Road Speed (km/hr), and Expected Delay Time (min.). The Expected Delay Time may be entered as a distribution. The Haul Time (min.) on the haul road is produced as a statistic. Common elements are used here to model the Haul Road processes.



Haul_Rout #445908

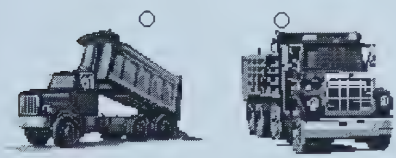
Parameters | Outputs | Statistics

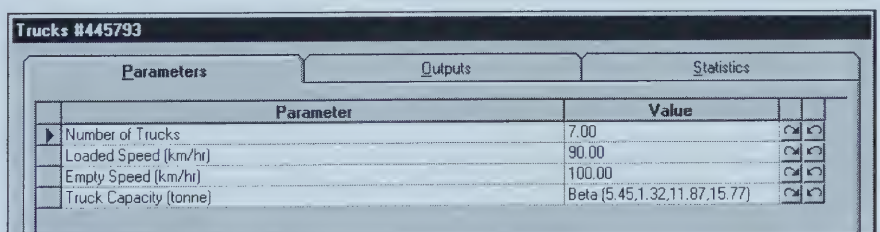
Parameter	Value
Haul Rout Name	Asphalt 1 (City)
Length of Haul Rout (km)	15.00
Average Haul Rout Speed Limit (km/hr)	60.00
Expected Delay Time	Triangular (5.00,10.00,25.00)

Figure 8: Haul Road Element

2.9 Aggregate / Asphalt Trucks Element

The Aggregate and Asphalt Truck Elements, shown in Figures 1 and 9, are used to represent the haul trucks for the Aggregate and Asphalt Operations. Although they are identical in everyway, an Asphalt Truck can only be used for the Asphalt Operation and visa versa for the Aggregate Operation. Their attributes include Number of Trucks, Loaded Speed (km/hr), Empty Speed (km/hr), and Truck Capacity (tonne). Common elements are used here to create the Asphalt and Aggregate Trucks.





Trucks #445793

Parameters | Outputs | Statistics

Parameter	Value
Number of Trucks	7.00
Loaded Speed (km/hr)	90.00
Empty Speed (km/hr)	100.00
Truck Capacity (tonne)	Beta (5.45,1.32,11.87,15.77)

Figure 9: Asphalt and Aggregate Haul Truck Elements

3.0 Creating a Model Using the SWRC Template

In order to create a simulation model using the SWRC Template, the Surface Works Operations Parent Element must be selected. This is done by selecting (by clicking once) the SWRC Parent Element Button from the "Element Toolbar", and then adding it to the screen (by clicking once any where on the screen) (Figure 10).

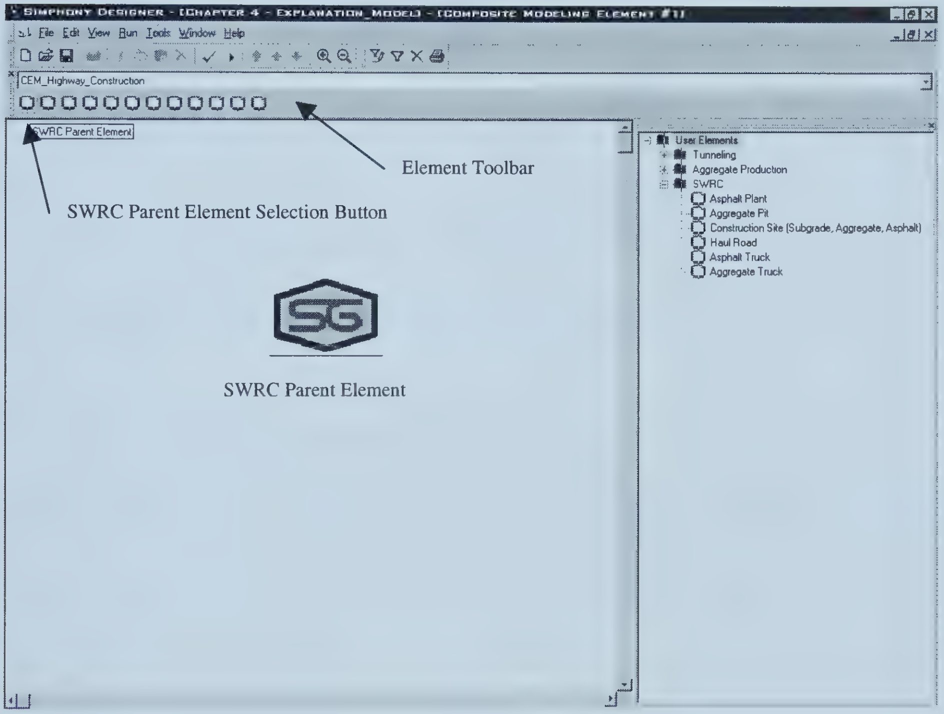


Figure 10: Selection of the SWRC Parent Element

The remainder of the elements of the model are created as "child elements" of the SWRC Parent Element. In order to create those elements, the user must enter the SWRC Parent Element's "Child Window" by "right clicking" over the element and selecting it from the list (Figure 11).

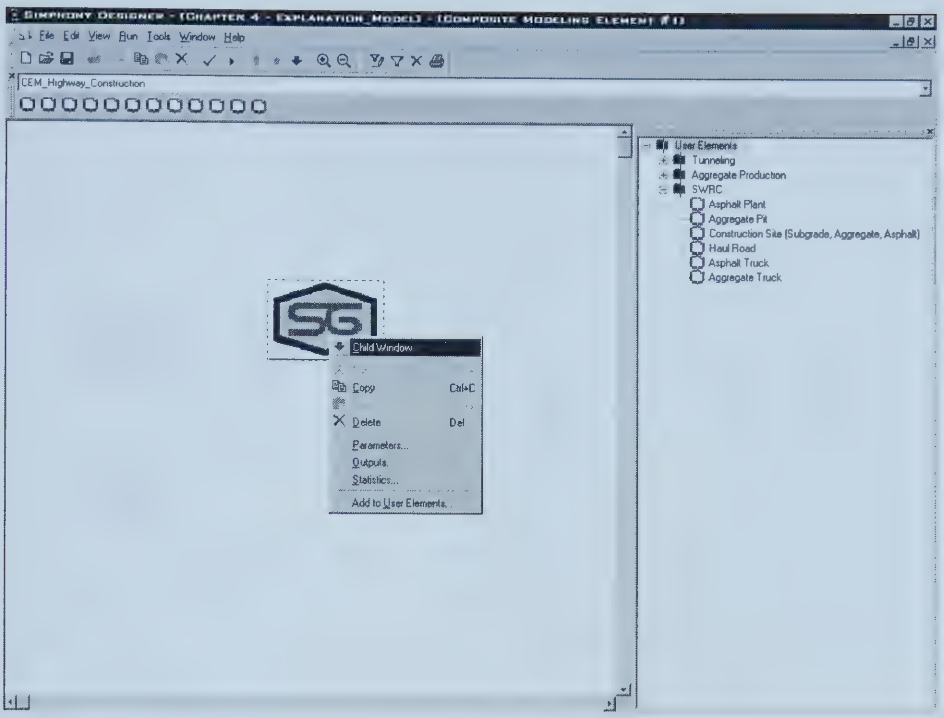


Figure 11: Entering the SWRC Parent Element Child Window

From the SWRC Parent Element's Child Window, the other elements of the model can be added. This is done by using Simphony's User Element Window. Each element, from the SERC user element folder is selected and "dragged" onto the screen (Figure 12).

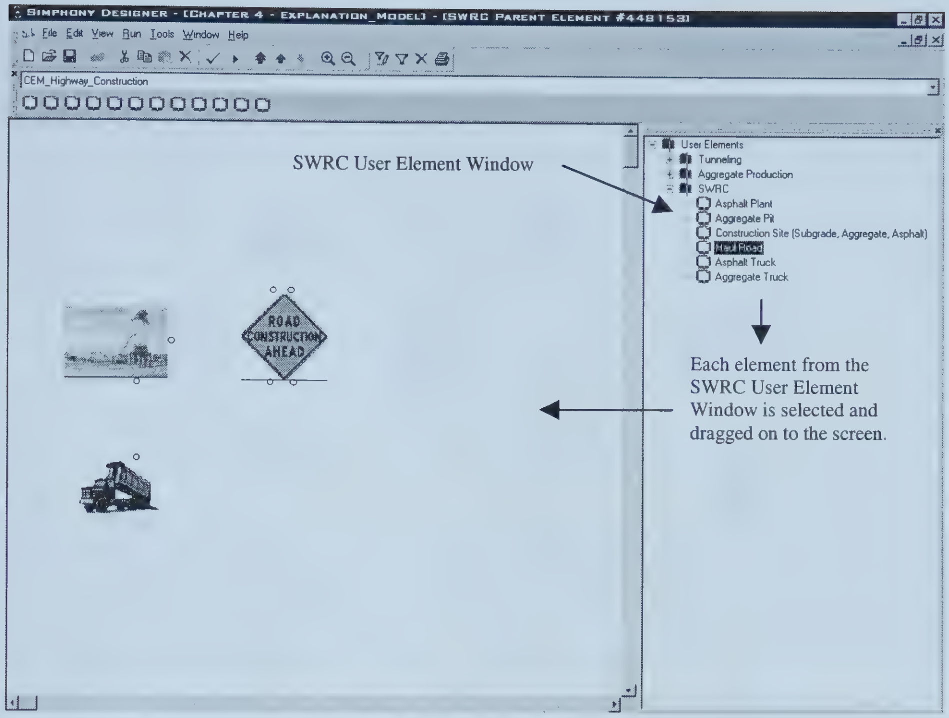


Figure 12: SWRC Parent Element Child Window: The User Element Window

Once all of the model elements have been created, they must be connected to one another, and their individual parameters must be entered, as described in Section 2. Figure 13 displays the general configuration of the model elements. Haul Road Elements are the only ones that can be used several times. For the asphalt haul cycle, for example, a haul route can be created to represent different sections of road (ex. rural & highway).

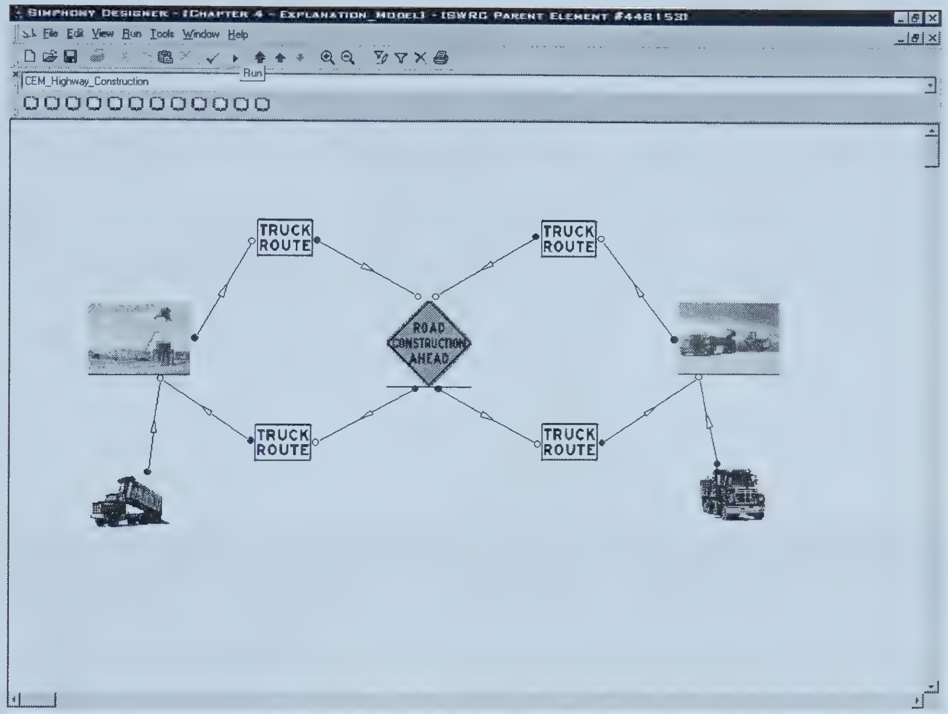


Figure 13: General Configuration of a SWRC Model

After all the appropriate parameters have been entered into each element the model can be simulated by pressing the "Run" button on Simphony toolbar. The simulation will proceed until the road construction is complete.

4.0 Model Outputs and Statistics

Each element in the SWRC Template produces some form of output or statistic, as described in Section 2. In the SWRC Template, outputs are viewed by "double-clicking" on the desired element, and selecting the "Outputs" tab. Figure 14 displays the outputs for the Construction Site Element.

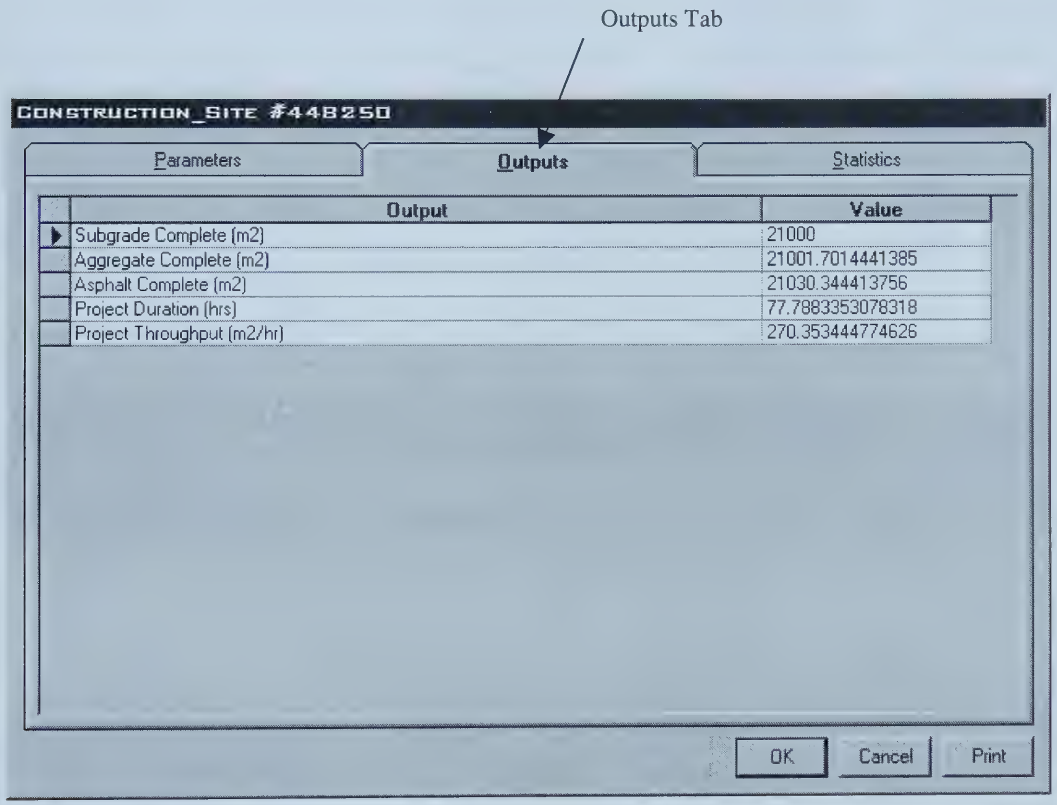


Figure 14: Output Tab for the Construction Site Element

Element statistics are found within the child window of each element. To access this window, select the desired element, "right click" and select Child Window from the list provided (Figure 15).

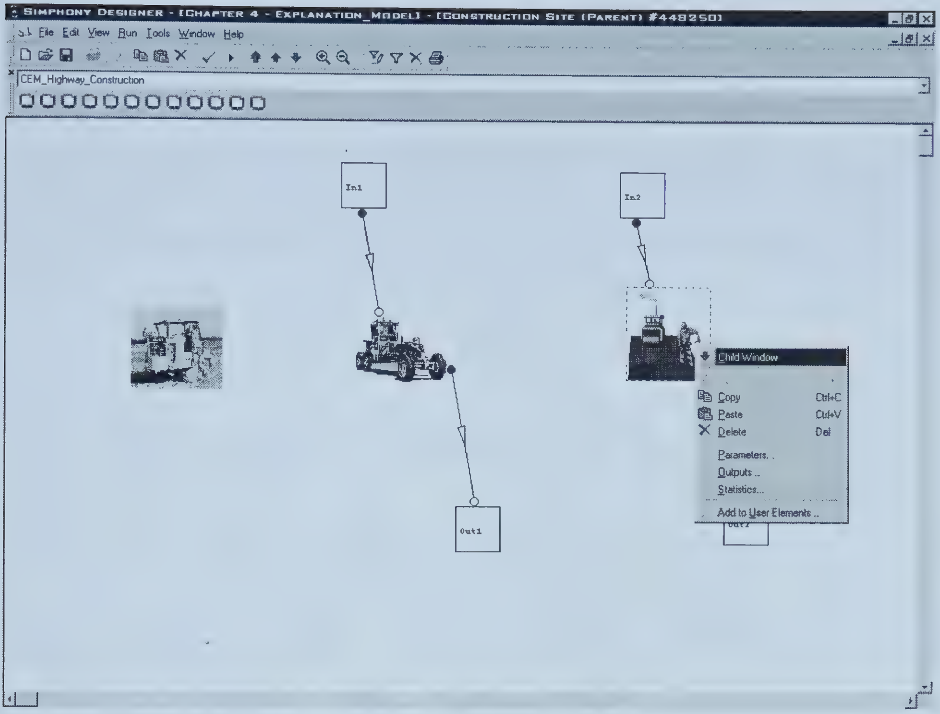


Figure 15: Selecting the Child Window for the Asphalt Placement Element

Figure 16 displays the Child Window of the Asphalt Placement Element. To view one of the statistical outputs, select it and "double-click".

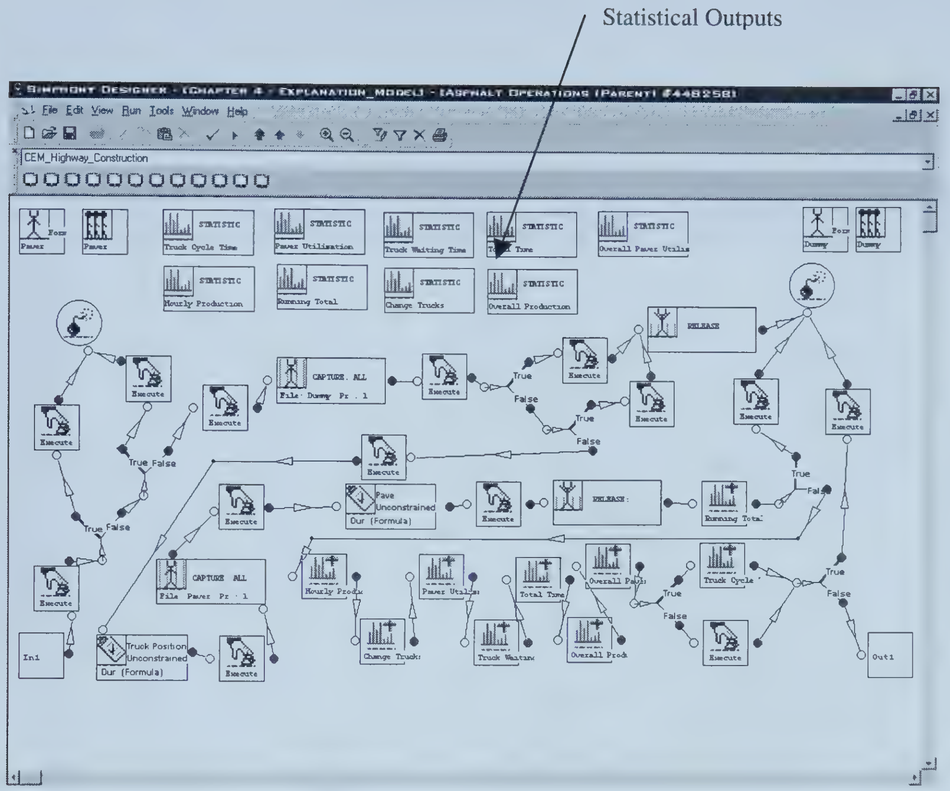


Figure 16: Child Window For The Asphalt Placement Element

Figure 17 displays an example of the Hourly Production statistic found within the Asphalt Placement Element. By selecting the “View” button, the statistic can be displayed graphically.

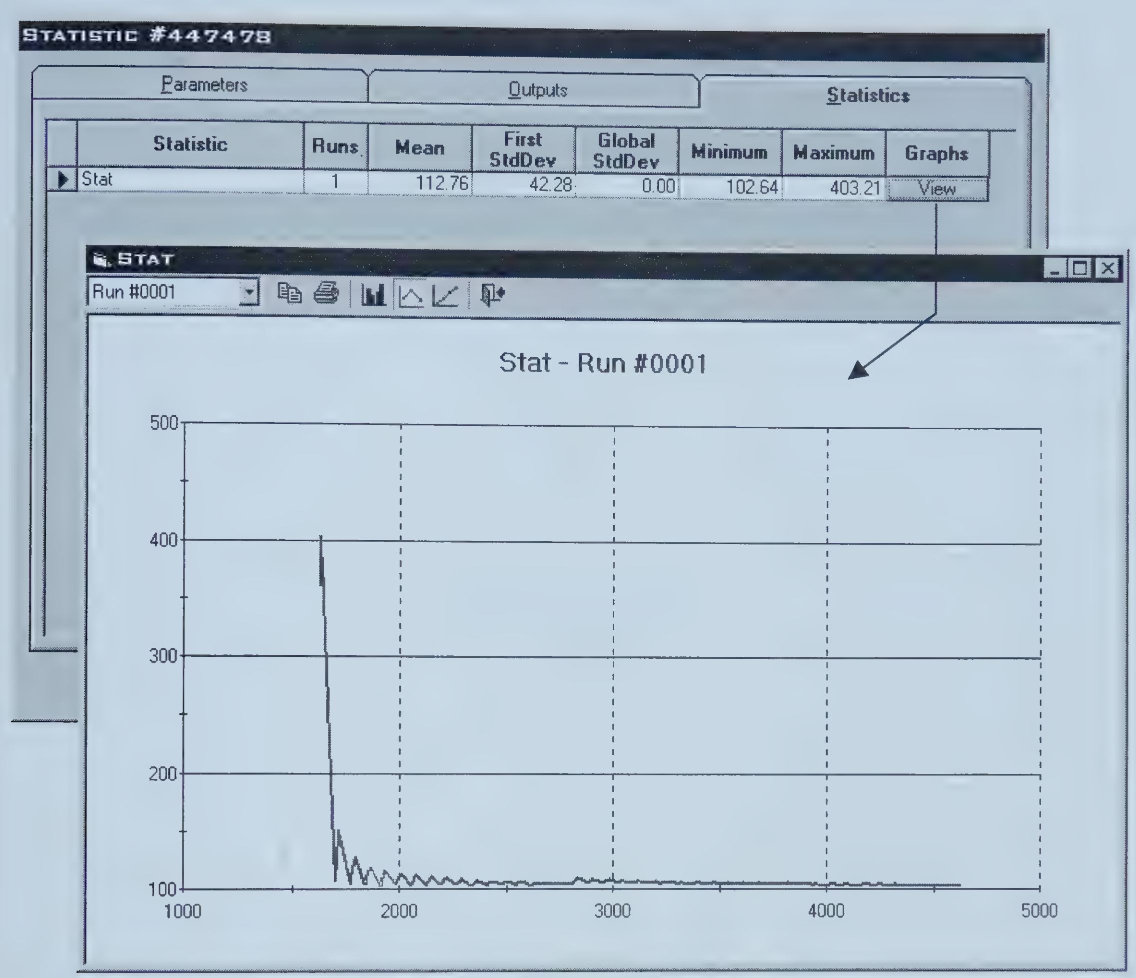


Figure 17: Hourly Production Statistic - Asphalt Placement Element

APPENDIX B

Simphony Code

Construction Site Element

```
Option Explicit

Public Function Construction_Site_OnCreate(ob As CFCSim_ModelingElementInstance,
x As Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Highway_Operation" Then
        MessagePrompt "This element can only be created as a child of the Highway
Operations parent element"
        Construction_Site_OnCreate = False
        Exit Function
End If

ob.OnCreate (x,y,True)
Construction_Site_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+125
ob.CoordinatesY(1)=y+125

ob.AddAttribute "Highway_Area","Highway Area (m2)",CFC_Numeric ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Subgrade_Complete","Subgrade Complete (m2)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Aggregate_Complete","Aggregate Complete (m2)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Highway_Complete","Asphalt Complete (m2)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Project_Duration","Project Duration (hrs)",CFC_Numeric ,CFC_Single
,CFC_ReadOnly
ob.AddAttribute "Through_Put","Project Throughput (m2/hr)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly

End Function

Public Sub Construction_Site_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Construction_Site_OnDraw(ob As CFCSim_ModelingElementInstance)
```

```
CDC.RenderPicture
"Road_Construction.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),125,127
ob.DrawConnectionPoints
If ob.Selected Then
	CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
	CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True

End Sub

Public Sub Construction_Site_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

ob("Subgrade_Complete") = 0
ob("Aggregate_Complete") = 0
ob("Highway_Complete") = 0

End Sub

Public Sub Construction_Site_OnSimulationPostRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

ob("Project_Duration") = SimTime/60
ob("Through_Put") = ob("Highway_Complete")/ob("Project_Duration")

End Sub
```

Subgrade Preparation Element

```
Option Explicit

Public Function Subgrade_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Construction_Site" Then
        MessagePrompt "This element can only be created as a child of the Construction
Site parent element"
        Subgrade_OnCreate = False
        Exit Function
End If

ob.OnCreate (x,y,True)
Subgrade_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+100
ob.CoordinatesY(1)=y+90

ob.AddAttribute "Subgrade_Production","Subgrade Production
(m2/hr)",CFC_Distribution ,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Subgrade_Complete","Subgrade Complete (m2)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Subgrade_Duration","Total Duration of Subgrade (hrs)",CFC_Numeric
,CFC_Single,CFC_ReadOnly
ob.AddAttribute "Production_Start_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Production_End_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "End_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Ave_Production","Subgrade Production (m2/hr)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly

End Function

Public Sub Subgrade_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Subgrade_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture "Mixer.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),100,92
```

```
ob.DrawConnectionPoints
If ob.Selected Then
        CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
        CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True

End Sub

Public Sub Subgrade_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
ob("End_Flag") = 0
ob("Production_End_Time") = 0
End Sub

Public Sub Subgrade_OnSimulationPostRun(ob As CFCSim_ModelingElementInstance,
RunNum As Integer)
ob("Subgrade_Complete") = ob.Parent ("Subgrade_Complete")
ob("Subgrade_Duration") = (ob("Production_End_Time") -
ob("Production_Start_Time"))/60
If ob("Subgrade_Duration") = 0 Then
ob("Ave_Production")= 0
Else
ob("Ave_Production")= ob.Parent ("Subgrade_Complete")/ob("Subgrade_Duration")
End If
End Sub
```

Aggregate Placement Element

```
Option Explicit

Public Function Aggregate_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Construction_Site" Then
	MessagePrompt "This element can only be created as a child of the Construction
Site parent element"
	Aggregate_OnCreate = False
	Exit Function
End If

ob.OnCreate (x,y,True)
Aggregate_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+100
ob.CoordinatesY(1)=y+70

ob.AddAttribute "Aggregate_Production","Grader Production Rate
(tonne/hr)",CFC_Distribution ,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Dumping_Time","Truck Dumping Time (min.)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Aggregate_Pull","Aggregate Pull (tonne/m2)",CFC_Numeric
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Subgrade_Buffer","Subgrade Operation Buffer (m2)",CFC_Numeric
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Dumped_Aggregate","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Total_Dumped","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Production_Start_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Production_End_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Temp_Time_Grader","",CFC_Numeric ,CFC_Single
,CFC_Hidden
ob.AddAttribute "Stat_Production_Time_Grader","",CFC_Numeric ,CFC_Single
,CFC_Hidden
ob.AddAttribute "Stat_Temp_Time_Labour","",CFC_Numeric ,CFC_Single
,CFC_Hidden
ob.AddAttribute "Stat_Production_Time_Labour","",CFC_Numeric ,CFC_Single
,CFC_Hidden
ob.AddAttribute "Tonnes_Placed","Aggregate Placed (tonnes)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
```

```
ob.AddAttribute "Aggregate_Duration","Total Aggregate Duration (hrs)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Ave_Production","Aggregate Production (tonne/hr)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Overall_Duration","Overall Aggregate Duration (hrs)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "End_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Start_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag2","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Difference","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Temp_Quantity","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Aggregate_Overall_Start","",CFC_Numeric ,CFC_Single
,CFC_Hidden
ob.AddAttribute "Overall_Temp_Quantity","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Overall_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden


End Function

Public Sub Aggregate_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Aggregate_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture "Aggregate.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),100,72
ob.DrawConnectionPoints
If ob.Selected Then
        CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
        CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True

End Sub

Public Sub Aggregate_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

ob("Dumped_Aggregate") = 0
ob("Production_Start_Time") = 0
ob("Stat_Temp_Time_Grader") = 0
```

```
ob("Stat_Production_Time_Grader") = 0
ob("Stat_Temp_Time_Labour") = 0
ob("Stat_Production_Time_Labour") = 0
ob("Tonnes_Placed") = 0
ob("Total_Dumped") = 0
ob("End_Flag") = 0
ob("Aggregate_Duration") = 0
ob("Start_Flag") = 0
ob("Production_End_Time") = 0
ob("Duration_Temp_Time") = 0
ob("Duration_Flag") = 0
ob("Duration_Flag2") = 0
ob("Aggregate_Overall_Start") = 0

End Sub

Public Sub Aggregate_OnSimulationPostRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
If ob("Production_Start_Time") = 0 Then
ob("Aggregate_Duration") = 0
ob("Ave_Production") = 0
ob("Overall_Duration") = 0
Else
ob("Aggregate_Duration") = ob("Aggregate_Duration")/60
ob("Ave_Production") = ob("Tonnes_Placed")/ob("Aggregate_Duration")
ob("Overall_Duration") = (ob("Production_End_Time") -
ob("Aggregate_Overall_Start"))/60
End If

End Sub
```

Asphalt Placement Element

```
Option Explicit

Public Function Asphalt_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Construction_Site" Then
	MessagePrompt "This element can only be created as a child of the Construction
Site parent element"
	Asphalt_OnCreate = False
	Exit Function
End If

ob.OnCreate (x,y,True)
Asphalt_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+90
ob.CoordinatesY(1)=y+100

ob.AddAttribute "Paver_Number","Number of Pavers",CFC_Numeric ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Asphalt_Production","Paver Advance Rate
(tonne/hr)",CFC_Distribution ,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Truck_Position","Truck Postioning Time (min.)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Asphalt_Pull","Asphalt Pull (tonne/m2)",CFC_Numeric ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Aggregate_Buffer","Aggregate Operation Buffer (m2)",CFC_Numeric
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Tonnes_Placed","Asphalt Placed (tonnes)",CFC_Numeric ,CFC_Single
,CFC_ReadOnly
ob.AddAttribute "Production_Start_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Production_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Asphalt_Duration","Total Asphalt Duration (hrs)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "End_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Ave_Production","Asphalt Production (tonne/hr)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Overall_Duration","Overall Asphalt Duration (hrs)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Production_End_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
```

```
ob.AddAttribute "Stat_Temp_Time2","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Change_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag2","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Difference","",CFC_Numeric ,CFC_Single,CFC_Hidden
ob.AddAttribute "Temp_Quantity","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Asphalt_Overall_Start","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Overall_Temp_Quantity","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Overall_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden

End Function

Public Sub Asphalt_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Asphalt_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture "Asphalt.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),90,102
ob.DrawConnectionPoints
If ob.Selected Then
	CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
	CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw Tru

End Sub

Public Sub Asphalt_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

ob("Tonnes_Placed") = 0
ob("Production_Start_Time") = 0
ob("Stat_Temp_Time") = 0
ob("Stat_Production_Time") = 0
ob("End_Flag") = 0
ob("Production_End_Time") = 0
ob("Stat_Temp_Time2") = 0
ob("Stat_Change_Time") = 0
ob("Duration_Temp_Time") = 0
ob("Asphalt_Duration") = 0
ob("Duration_Flag") = 0
```

```
ob("Duration_Flag2") = 0
ob("Asphalt_Overall_Start") = 0

End Sub

Public Sub Asphalt_OnSimulationPostRun(ob As CFCSim_ModelingElementInstance,
RunNum As Integer)
If ob("Production_Start_Time") = 0 Then
ob("Asphalt_Duration") = 0
ob("Ave_Production") = 0
ob("Overall_Duration") = 0
Else
ob("Asphalt_Duration") = ob("Asphalt_Duration")/60
ob("Ave_Production") = ob("Tonnes_Placed")/ob("Asphalt_Duration")
ob("Overall_Duration") = (SimTime - ob("Asphalt_Overall_Start"))/60
End If

End Sub
```

<u>Asphalt Plant Element</u>

```
Option Explicit

Public Function Asphalt_Plant_OnCreate(ob As CFCSim_ModelingElementInstance, x
As Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Highway_Operation" Then
        MessagePrompt "This element can only be created as a child of the Highway
Operations parent element"
        Asphalt_Plant_OnCreate = False
        Exit Function
End If

ob.OnCreate (x,y,True)
Asphalt_Plant_OnCreate = True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+150
ob.CoordinatesY(1)=y+105


ob.AddAttribute "Production_Rate","Rate of Production (tonne/hour)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Truck_Load_Time","Load Time per Truck (min.)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Truck_Prep_Time","Truck Preparation Time (min.)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Storage_Capacity","Storage Capacity (tonne)",CFC_Numeric
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Inventory","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Aggregate_Buffer","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Running_Total","Total Asphalt Produced (tonne)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Stat_Production_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Production_Start_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Production_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Asphalt_Duration","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag2","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Asphalt_Overall_Start","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Overall_Temp_Quantity","",CFC_Numeric ,CFC_Single ,CFC_Hidden
```

```
ob.AddAttribute "Overall_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden

End Function

Public Sub Asphalt_Plant_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Asphalt_Plant_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture
"Asphalt_Plant.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),149,104
ob.DrawConnectionPoints
If ob.Selected Then
        CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
        CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True
End Sub

Public Sub Asphalt_Plant_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

ob("Running_Total") = 0
ob("Inventory") = ob("Storage_Capacity")
ob("Stat_Production_Time") = 0
ob("Stat_Temp_Time") = 0
ob("Production_Start_Time") = 0
ob("Production_Time") = 0
ob("Asphalt_Duration") = 0
ob("Duration_Temp_Time") = 0
ob("Duration_Flag") = 0
ob("Duration_Flag2") = 0
ob("Asphalt_Overall_Start") = 0

Dim childob As CFCSim_ModelingElementInstance
        For Each childob In Elements
                If childob.ElementType = "Asphalt" Then
                        ob("Aggregate_Buffer") = childob("Aggregate_Buffer")
                End If
        Next

End Sub
```

Aggregate Pit Element

```
Option Explicit
Public Function Gravel_Pit_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Highway_Operation" Then
        MessagePrompt "This element can only be created as a child of the Highway
Operations parent element"
        Gravel_Pit_OnCreate = False
        Exit Function
End If

ob.OnCreate (x,y,True)
Gravel_Pit_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+150
ob.CoordinatesY(1)=y+105

ob.AddAttribute "Truck_Loading_Rate","Truck Loading Rate
(tonne/hour)",CFC_Distribution ,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Truck_Prep_Time","Truck Preparation Time (min.)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Running_Total","Total Aggregate Loaded (tonne)",CFC_Numeric
,CFC_Single ,CFC_ReadOnly
ob.AddAttribute "Subgrade_Buffer","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Production_Start_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Stat_Production_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Aggregate_Duration","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Duration_Flag2","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Aggregate_Overall_Start","",CFC_Numeric ,CFC_Single
,CFC_Hidden
ob.AddAttribute "Overall_Temp_Quantity","",CFC_Numeric ,CFC_Single ,CFC_Hidden
ob.AddAttribute "Overall_Temp_Time","",CFC_Numeric ,CFC_Single ,CFC_Hidden

End Function

Public Sub Gravel_Pit_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw
```

```
End Sub

Public Sub Gravel_Pit_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture
"Agg_Source_3.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),149,105
ob.DrawConnectionPoints
If ob.Selected Then
        CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
        CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True
End Sub

Public Sub Gravel_Pit_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

ob("Running_Total") = 0
ob("Production_Start_Time") = 0
ob("Stat_Temp_Time") = 0
ob("Stat_Production_Time") = 0
ob("Aggregate_Duration") = 0
ob("Duration_Temp_Time") = 0
ob("Duration_Flag") = 0
ob("Duration_Flag2") = 0
ob("Aggregate_Overall_Start") = 0

Dim childob As CFCSim_ModelingElementInstance
        For Each childob In Elements
                If childob.ElementType = "Aggregate" Then
                        ob("Subgrade_Buffer") = childob("Subgrade_Buffer")
                End If
        Next

End Sub
```

Haul Truck Element (Aggregate & Asphalt)

```
Option Explicit

Public Function Trucks_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Highway_Operation" Then
        MessagePrompt "This element can only be created as a child of the Highway
Operations parent element"
        Trucks_OnCreate = False
        Exit Function
End If

ob.OnCreate (x,y,True)
Trucks_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+125
ob.CoordinatesY(1)=y+75

ob.AddAttribute "Truck_Number","Number of Trucks",CFC_Numeric ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Loaded_Speed","Loaded Speed (km/hr)",CFC_Numeric ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Empty_Speed","Empty Speed (km/hr)",CFC_Numeric ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Truck_Capacity","Truck Capacity (tonne)",CFC_Distribution
,CFC_Single ,CFC_ReadWrite

End Function

Public Sub Trucks_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Trucks_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture
"Asphalt_Truck.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),125,78
ob.DrawConnectionPoints
If ob.Selected Then
```

```
        CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
        CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True


End Sub
```

Haul Road Element

```
Option Explicit

Public Function Haul_Rout_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

If ob.Parent.ElementType <> "Highway_Operation" Then
        MessagePrompt "This element can only be created as a child of the Highway
Operations parent element"
        Haul_Rout_OnCreate = False
        Exit Function
End If

ob.OnCreate (x,y,True)
Haul_Rout_OnCreate=True

ob.SetNumCoordinates 2
ob.CoordinatesX(0)=x
ob.CoordinatesY(0)=y
ob.CoordinatesX(1)=x+85
ob.CoordinatesY(1)=y+60

ob.AddAttribute "Haul_ID","Haul Rout Name",CFC_Text ,CFC_Single
,CFC_ReadWrite
ob.AddAttribute "Haul_Length","Length of Haul Rout (km)",CFC_Numeric
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Haul_Speed","Average Haul Rout Speed Limit (km/hr)",CFC_Numeric
,CFC_Single ,CFC_ReadWrite
ob.AddAttribute "Haul_Delay","Expected Delay Time",CFC_Distribution ,CFC_Single
,CFC_ReadWrite

End Function

Public Sub Haul_Rout_OnDragDraw(ob As CFCSim_ModelingElementInstance)

ob.OnDraw

End Sub

Public Sub Haul_Rout_OnDraw(ob As CFCSim_ModelingElementInstance)

CDC.RenderPicture "Truck_Rout.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),85,62
ob.DrawConnectionPoints
If ob.Selected Then
        CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
```

```
        CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
End If
'ob.OnDraw True

End Sub
```